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National Aeronautics
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SUMMARY

A modified version of a rod-wall sound shield was tested in the Mach 5 pilot quiet tunnel at the Langley Research Center over a range of unit Reynolds numbers from 1.0×10^7 to 3.5×10^7 per meter. The walls of the rectangular model consisted of a sharp flat leading-edge plate followed by longitudinal rods with gaps between the rods for boundary-layer suction. Details of model construction and previous results are given in NASA TP-1672. The model was modified by inclining the leading-edge plates to produce an initial 2° expansion for the purpose of ascertaining the sensitivity of boundary-layer transition to leading-edge disturbances. Rod-surface pitot pressures, mean free-stream pitot pressures and static pressures on the rods and plenum walls were measured. Hot-wire measurements were also made in the model and nozzle free stream at a unit Reynolds number of 1.5×10^7 per meter. The surface pitot pressures indicated that transition was much farther forward than for the previous tests due to the leading-edge modification and minor fabrication flaws in the model.

Early boundary-layer transition on the rods was confirmed by hot-wire measurements which showed much higher noise levels in the free-stream shield flow when compared with results from previous tests. Mean pitot-pressure surveys within the shielded region inside the model indicated that there was an overexpansion and recompression that would effectively limit the streamwise length of undisturbed flow to about 13 cm along the centerline.

INTRODUCTION

Turbulent boundary layers on the walls of supersonic and hypersonic wind tunnels radiate noise (refs. 1 to 3) which will (when incident on the test model) cause premature transition in the model boundary layer. Thus, in order to keep the model boundary-layer laminar at higher Reynolds numbers (one objective of the quiet tunnel development program (ref. 4)), the radiated noise must be reduced or eliminated from the test region. One way of reducing the noise level is to surround the test region with some device which allows the air to flow over the model at the desired test conditions but will protect or shield the model from noise radiated by the tunnel-wall boundary layer.

Several shields have been tested at the Langley Research Center as reported in references 4 to 7. The first shield tested was a flat panel which consisted of a sharp leading edge with longitudinal rods spaced a finite distance apart so that the rod boundary layers could be laminarized by suction between the rods (refs. 5 to 7). The data for the flat rod panel indicated that noise levels in the shielded region were reduced significantly up to a Reynolds number of approximately 8×10^6 per meter based on the length of a hypothetical quiet test region (ref. 4).

An axisymmetric shield was tested next, but the mean flow field in this shield was highly nonuniform, caused by the centerline focusing of the leading-edge shocks (ref. 4). A rectangular rod-wall sound shield was then designed and tested. This model eliminated the centerline focusing problem, but the "open" leading-edge design used in the first two models tested resulted in noise levels higher than desirable (ref. 4). This model was then modified with sharp flat-plate leading edges, and two different fairings from the flat leading edge to the rods were tested; but the noise levels were still unacceptable due to premature transition in the rod boundary layers. The next model tested was referred to as "Mod V" and is described in detail in reference 8. The principal modification for this model was in the fairing region between the sharp flat leading edges and the circular rods. This new fairing was designed to maintain a constant-flow cross-section area as suction was initiated and air was removed through the streamwise gaps between the rods. Test results (ref. 8) indicated that at low free-stream Reynolds numbers ($R_\infty \leqq 1.6 \times 10^7$ per meter) transition occurred farther downstream on the rods, and the local free-stream noise levels were reduced. At higher free-stream Reynolds numbers ($R_\infty \geqq 1.6 \times 10^7$ per meter) some of the rod boundary layers were turbulent at or ahead of the acoustic origins corresponding to probe stations in the flow, and the noise levels were increased due to high-frequency noise radiation from the very thin rod boundary layers.

One possible cause of transition in the rod boundary layers at the higher Reynolds numbers was the intersection of the fairly strong leading-edge shocks with the rods. These leading-edge shocks are always present and are caused by the finite leading-edge thickness and the hypersonic boundary-layer displacement effects near the leading edge. The next modification which is the subject of this report and will be referred to as "Mod VI" was designed to weaken these leading-edge shocks. This latest model utilizes the same leading edge and rod fairings as Mod V, but the leading-edge plates are inclined inward by 2° to produce an expansion at the leading edge in an attempt to weaken or at least modify the leading-edge shocks.

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SYMBOLS

M Mach number

p static pressure

p_o stagnation pressure

p_t pitot pressure

$p_{t,w}$ surface pitot pressure on rods

R_e local unit Reynolds number per meter

R_x local free-stream Reynolds number based on wetted length from leading edge

R_∞ free-stream unit Reynolds number per meter

x distance from model leading edge (axial), cm

y vertical distance normal to model centerline, cm (this was incorrectly defined in ref. 8)

z horizontal distance normal to model centerline, cm (this was incorrectly defined in ref. 8)

β shock angle, deg

δ boundary-layer thickness, cm

μ Mach angle, deg

Subscripts:

a acoustic-origin location

box vacuum-chamber condition

e local value at edge of boundary layer

p probe location

T transition location

w value at surface

∞ free-stream condition

Superscripts:

$\sim$ root-mean-square (rms) value

$-$ mean value

APPARATUS AND TESTS

The tests were made in the Mach 5 pilot quiet tunnel at the Langley Research Center (refs. 9 and 10). This tunnel (fig. 1(a)) consists of a settling chamber, a Mach 5 axisymmetric nozzle, an open-jet test section within a vacuum chamber, and a diffuser section. The general layout of the tunnel and the operating conditions are described in reference 9. The Mach 5 axisymmetric nozzle incorporates a boundary-layer suction slot just upstream of the throat. The purpose of the slot is to bleed off the settling-chamber turbulent boundary layer before it enters the nozzle so that a laminar boundary

layer can be maintained on the downstream nozzle wall to higher Reynolds numbers (ref. 10). However, for the present tests, the bleed valves were closed. The slot lip then trips the nozzle-wall boundary layer so that the "transition peak" (ref. 11) in the nozzle input noise occurs at a much lower Reynolds number, which is below the range of interest for these tests.

A schematic representation of the rod-wall sound shield mounted in the tunnel is shown in figure 1(a). Additional details and views of the model are shown in figures 1(b) to (d). The only difference between Mod V (ref. 8) and the present model, designated as Mod VI, is the 2° expansion angle in the model leading edge (fig. 1(d)). All four of the leading edges are inclined inward as shown in figure 1(d). The flow would then be expanded 2° at the leading edge, and the strength of the leading-edge shocks within the rod-wall model should be reduced.

Surface pitot pressures on the rods were measured with a three-tube pitot rake shown in figure 2. A traversing mechanism was used to move the pressure rake during a test run. Mean free-stream pitot pressures were measured inside the rod-wall sound shield in the vertical centerplane of the model with another three-tube rake.

Hot-wire data, using a constant current anemometer, were obtained in the rod-wall sound shield. The data-reduction techniques and probe design are described in reference 12.

Static pressures were measured on the flow side and the plenum side of the rods and in the gaps between selected rods. Static pressures were also measured on the plenum wall near the leading edge of the rod-wall model and on the nozzle wall. Tests were conducted at a nominal free-stream Mach number of 5 and at a range of R_{∞} from 1.0×10^{7} to 3.5×10^{7} per meter. The stagnation temperature was maintained at levels high enough to avoid condensation effects in the shield flow.

RESULTS AND DISCUSSION

Static Pressures

To assess the overall mean flow performance of the model, static pressures were measured on the upper and lower rod surfaces on the bottom panel of the rod-wall model. Plenum and vacuum-chamber static pressures were also measured. These static pressures, normalized by the static pressure measured on the nozzle surface at a point 1.8 cm upstream of the nozzle exit where flow-separation effects were never experienced, are shown in figure 3. Static pressures within the plenum should be less than 0.53 of free-stream static pressure in order for sonic cross flow to exist in the gaps between the rods. Sonic cross flow between the rods is desirable to reduce the plenum noise that may enter the internal shielded region of the rod-wall sound shield. Static pressures measured within the plenum were always less than 0.53 of free-stream pressure. Pressures on the bottom sides of the rods were generally lower than plenum pressures except for the forward station at the two lower unit Reynolds numbers.

As stated in reference 8, the cross flow for this forward station is presumably reduced for these conditions and some plenum noise could enter the shielded flow. The internal flow in the shield was not significantly disturbed, as shown by the top or flow-side rod static pressures (fig. 3(b)). The data of figure 3(b) indicate that the flow over the internal shielded region of the rod-wall shield is sufficiently uniform for the present purposes.

A knowledge of the conditions of the boundary layer within the nozzle is of importance when trying to analyze data within the rod-wall sound shield. If the nozzle boundary layer is separated far enough into the nozzle, then this turbulent boundary layer may enter the model and cause early transition in the rod-wall sound shield. It was established (ref. 8) that if the box pressure did not exceed 3.1 times the free-stream static pressure at a point 1.28 cm upstream of the nozzle exit, then the nozzle boundary layer would not separate and contaminate the model flow field. Box pressure is shown in figure 3(b) to be no greater than 3.0 times the free-stream pressure. For these conditions, the nozzle boundary layer should not enter into the model flow field, as shown in figure 4 where δ is based on pitot-pressure surveys in reference 4 which indicates that δ is essentially constant over the range of R_{∞} from 7×10^6 to 30×10^6 per meter.

Free-Stream Pitot Pressures

Free-stream pitot pressures were measured within the rod-wall sound shield by using a three-tube rake. The pitot probe was mounted on a traversing mechanism so that an axial survey of approximately 15.0 cm could be made during one run. In order to obtain the pressure survey with the 48-cm length of the model, three separate tunnel runs were required.

Pitot-pressure measurements with the rake in the vertical position are presented in figure 5. Also shown in figure 5 are the corresponding pitot-pressure surveys for Mod V (figs. 6(a) to (c) of ref. 8). As stated previously, the model used in the present investigation differed from the model of reference 8 only by having the leading edges inclined inward 2° which was expected to produce weaker leading-edge shocks. The data of figure 5 do indicate that the leading-edge shocks were weaker (based on the pressure increase to the peak levels) when compared with the previous data for Mod V at all test Reynolds numbers. However, there is a stronger centerline overexpansion and recompression at approximately 24 cm than observed in Mod V. At unit Reynolds numbers greater than 1.0×10^7 per meter, the overexpansion and recompression at 24 cm is stronger both on and off the centerline. Therefore, the present model has a region of relatively uniform flow (with small gradients) of only about 13 cm in length along the centerline starting at $x = 27$ cm compared with a core length of about 16 cm starting at $x = 22$ cm in Mod V.

Transition

Figure 6 shows a view of the top and bottom panels of the rod-wall model. The projected location of the leading-edge shocks with an angle of 12.9° (based on the average rise to peak pressure from the data of fig. 5) and the Mach lines

with an angle of μ of 11.8° are also shown. Also shown in figure 6 is an approximate locus of the "acoustic origins" (ref. 12) on the panel for a typical probe location at x_p = 33.0 cm and 25.9 cm on the model centerline. This locus is a hyperbola which is the intersection of a Mach cone with the panel surface with the vertex of the cone at the probe tip on the shield centerline at x_p = 33.0 cm. Both top and bottom surface rods are numbered in figure 6.

The location of transition on the flow side of the rods as indicated in figure 6 was based on surface-pitot data. The relation between these transition locations and the acoustic-origin curves will be discussed with the presentation of the hot-wire probe data. Details of the surface-pitot data are given in the following paragraphs.

Typical distributions of $p_{t,w}/p_o$ along the bottom rods 1, 3 to 6, and 8 are shown in figure 7. Typical distributions of $p_{t,w}/p_o$ for the top rods 1,1, 3,3 to 6,6, and 8,8 are shown in figure 8. For comparison purposes the transition locations for Mod V (solid symbols) from reference 8 are included in figures 7 and 8. The approximate locations of the pressure rise due to the leading-edge fairing are indicated in figure 7. The location of transition, denoted by the cross-hatched areas, is taken as the region where the surface pitot pressure begins to increase with increasing downstream distance. In general, the designated location of transition moves forward as the unit Reynolds number is increased. The surface-pitot-probe data are subject to uncertainties caused by small random lateral displacement of the probe tip which would affect the pitot reading significantly because of the very thin boundary layers on the rods ($\delta \cong$ 0.06 cm to 0.09 cm). Leading-edge shocks may be a problem along with other flow disturbances, such as mismatched rods. Examples are evident in figure 7(b) where the mismatched rod junctions caused a large increase in $p_{t,w}/p_o$ at x = 8 or 9 cm and in figure 7(d) where the leading-edge plate disturbance was unusually large. This disturbance is caused primarily by the effective 3° compression at the surface joint between the leading edge and the rods (fig. 1(d)). Also, there was a mismatch between the leading-edge plate and rod 5 (fig. 6) which acted as a boundary-layer trip. This irregular joint was quite effective in tripping the thin boundary layer (fig. 7(d)). Figure 8 is a presentation of the surface pitot pressure ($p_{t,w}/p_o$) for the top rods (1,1; 3,3 to 6,6; and 8,8). From comparing the data of figure 8 with that of figure 7 it can be seen that the top rods do not provide an exact duplicate of the data of figure 7, but there is sufficient evidence to indicate that, in general, transition occurrence is similar to that on the bottom rods and much farther forward than in Mod V.

The data of figure 7 at the acoustic-origin locus for the fluctuating pitot probe on the model centerline at x_p = 33.0 cm is shown plotted against unit Reynolds number in figure 9. If transition in the rod boundary layer contributes to the noise levels in the shield, then the noise levels at this probe location of x_p = 33.0 cm may be expected to be higher than the noise levels at corresponding stations in Mod V (see ref. 8) since transition has occurred on all rods, except possibly rod 3, for $R_\infty \geqq 1.6 \times 10^7$ per meter as evidenced by the increase in $p_{t,w}/p_o$ above a nominal laminar level of approximately 0.004 which is based on the results of reference 8.

Transition location from the surface-pitot data on rods 1, 4, and 6 of the present rod-wall sound shield (Mod VI) are compared in figure 10 with data from Mod V (ref. 8), the test panel of references 4 and 6, and flat-plate data. These previous models are described in the cited reference. The only difference between Mod V and Mod VI is the 2° inclined leading edge of Mod VI. The transition results for Mod V (ref. 8) compared with the results of the present data (figs. 6 to 8) indicate that the 2° inclined leading edge results in transition moving farther forward on the rods. As discussed previously, the probable cause of early transition on Mod VI is the flat-plate leading-edge disturbances (that is, the 3° compression at the leading-edge rod junction fig. 1(d)).

Hot-Wire Noise Measurements

A constant current hot-wire anemometer was used in the present rod-wall sound shield (Mod VI) to determine the fluctuating rms pressure disturbances on the model centerline. For comparison with previous data on Mod V these data are presented in figure 11 as normalized pitot-pressure fluctuations. (See ref. 12.) A schematic drawing, showing a side view of the model with the leading edge positioned 0.64 cm inside the Mach 5 nozzle, is presented in figure 11. The purpose of the rod-wall sound shield is to eliminate or shield a model from pressure fluctuations originating in the wind-tunnel-wall boundary layer. In this case the shielded region occurs behind the leading-edge shocks. Any pressure fluctuation, or noise, must enter the shield from stations well upstream of the model, since the noise is propagated along Mach lines. Four typical probe stations at $x_p = 22.9$, 27.9, 33.0, and 38.1 cm are designated by points 1 to 4 on the shield centerline. Present sound-reflection theory (ref. 7) on noise propagation and reflection in supersonic shields predicts that the local-stream noise at any of these stations would consist mostly of noise originating at or reflected from corresponding regions on the shield wall. These regions are also designated by points 1 to 4 on the bottom wall at the average streamwise location of the corresponding acoustic origins for the four probe stations. (The acoustic-origin locus for probe stations $x_p = 33.0$ cm and 25.9 cm is shown in fig. 6.) The reflected noise originates upstream of the model in the vicinity of the corresponding points on the nozzle centerline. All data shown in figure 11 are for $R_{\infty} \cong 1.5 \times 10^{7}$ per meter.

A complete survey inside the nozzle using the hot wire was not attempted for this investigation. As figure 11 indicates, the data at the three stations inside the Mach 5 nozzle are in good agreement with data from reference 8. Therefore, it is concluded that the present hot-wire probes and data-reduction techniques give results comparable to those of reference 8. Since the noise levels for Mod VI are all larger than those for Mod V, it is clear that the probe is responding to noise radiation from the rod boundary layers even at the most forward probe station of 25.4 cm. Examination of the transition pattern for $R_{\infty} \cong 1.6 \times 10^{7}$ per meter, as shown in figure 6, and comparison of that pattern with the acoustic-origin locus for $x_p = 25.9$ cm (obtained by simply translating the curve for $x_p = 33.0$ cm forward 7.1 cm) show that the flow along the rods facing into the shielded region should be laminar under these conditions. Thus, it may be concluded that although the boundary layer on the center or "stagnation line" of the rods is laminar according to surface-pitot-pressure surveys, the boundary layer in the gaps between the rods or off the

stagnation line is transitional or turbulent at $R_\infty \cong 1.6 \times 10^7$ per meter along the acoustic-origin locus for $x_p = 25.4$ cm. This particular type of transition behavior has been observed and discussed previously on the flat rod-wall panel (ref. 7). Thus, the forward movement of transition on Mod VI as compared with that on Mod V is the cause of the much higher noise levels in Mod VI as shown in figure 11.

CONCLUDING REMARKS

A rod-wall sound-shield model was tested at Mach 5 over a range of unit Reynolds numbers from 1.0×10^7 to 3.5×10^7 per meter. The model, which had a sharp flat-plate leading edge inclined 2° towards the model centerline, was one of a series of models constructed to determine the most effective way to reduce pressure fluctuations (noise) within the wind-tunnel flow core.

Static-pressure measurements in the nozzle, the test chamber, the model vacuum plenum, and on the rods showed that the flow in the shield was fully started over the range of test conditions. Sonic flow was maintained in the gap except near the leading edge for the lowest Reynolds number. Mean pitot-pressure surveys within the shielded region inside the model indicated that there was a small centerline expansion and recompression that would effectively limit the undisturbed flow core to about 13 cm.

Transition was obtained in the rod boundary layers from surface-pitot-pressure surveys along the windward ray of the rods. Comparison of these data with results from previous tests showed that transition occurred much farther forward than in all previous tests. Transition was believed to be caused by the sharp leading edge being inclined inward 2° and some fabrication flaws. Early boundary-layer transition on the rods was confirmed by a much larger fluctuating pressure level when compared with results from previous tests as measured by the hot-wire method.

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March 25, 1981

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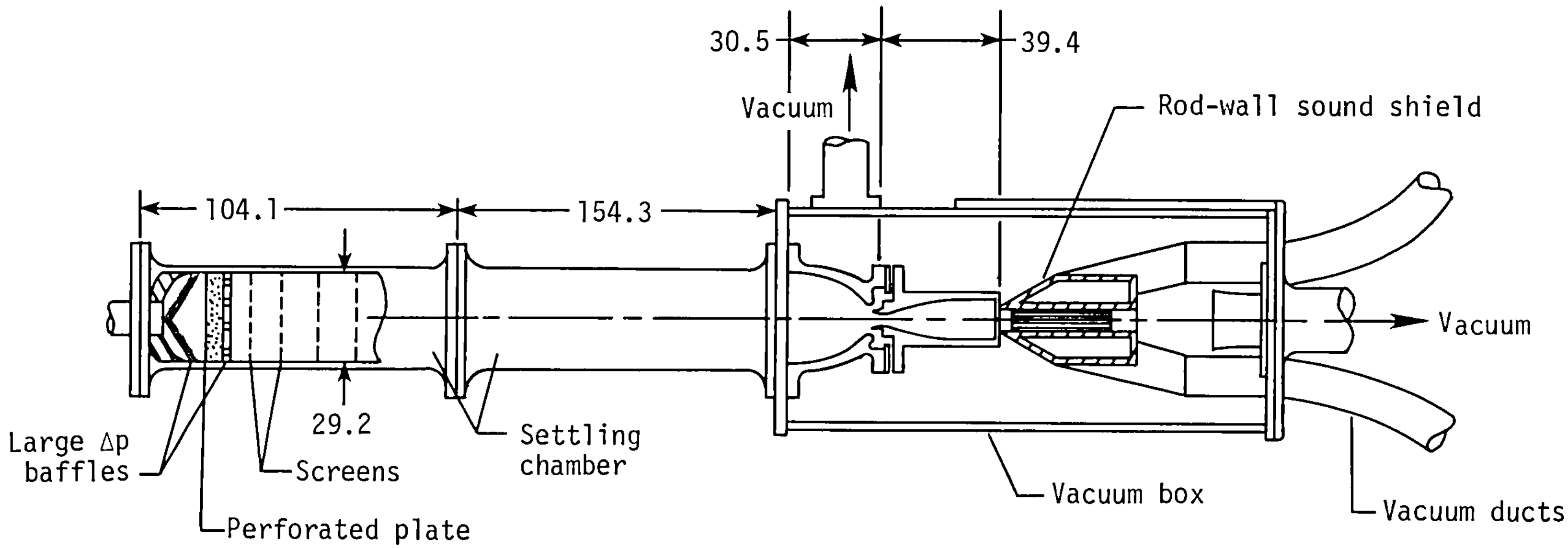
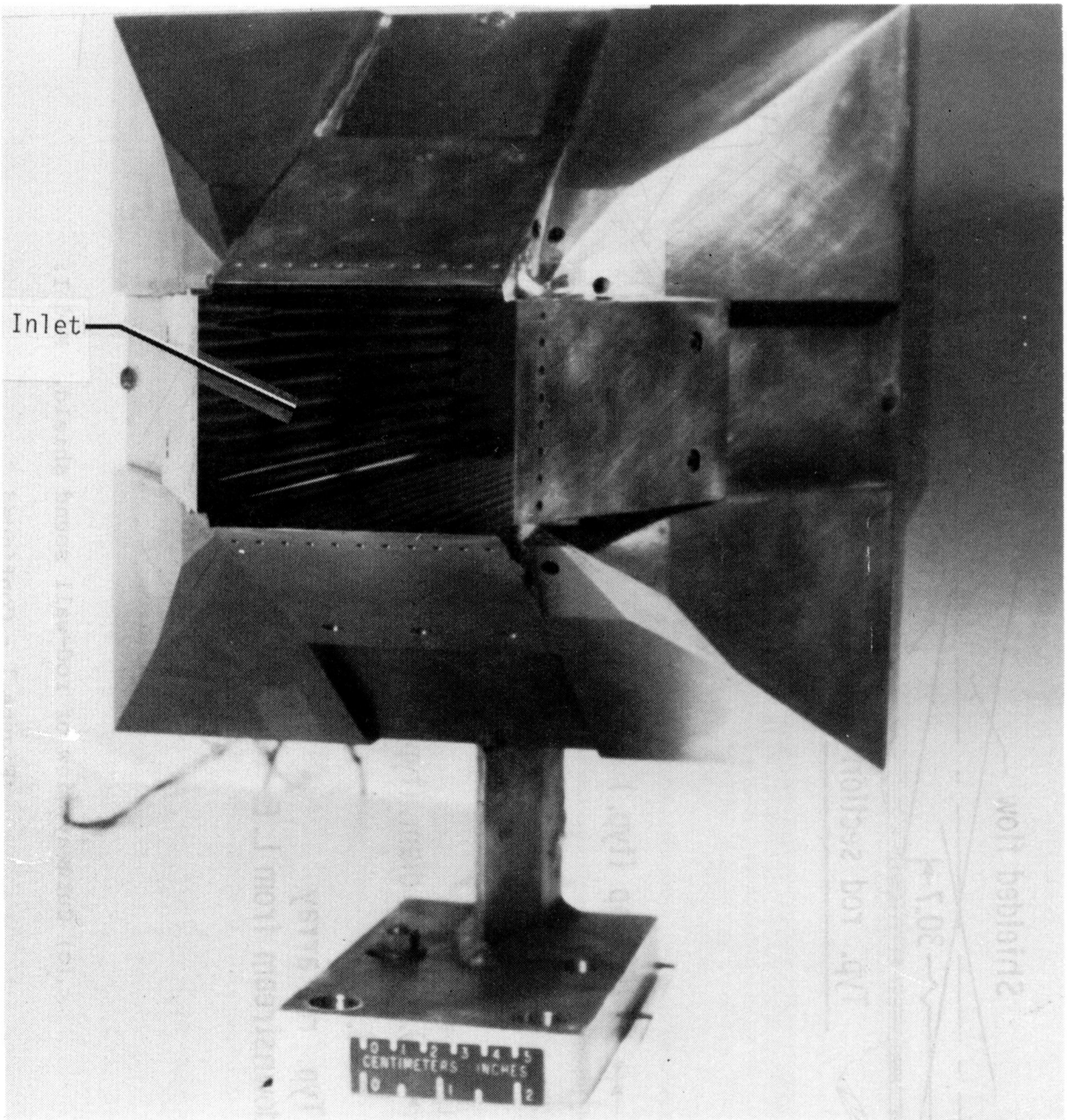


(a) Schematic drawing of test facility showing location of rod-wall sound shield.

Figure 1.- General arrangement of test facility and rod-wall sound shield. Dimensions are in centimeters.



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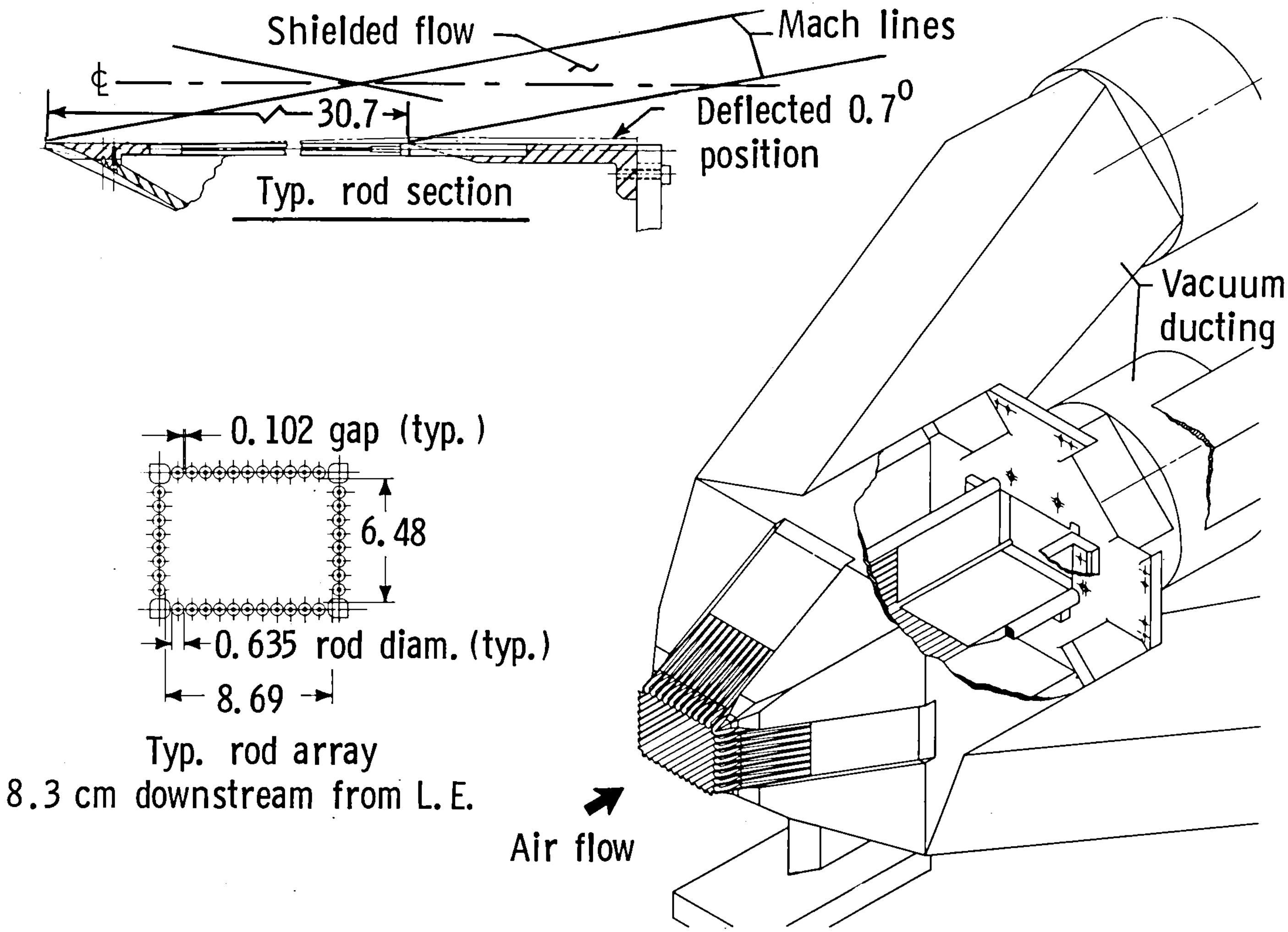
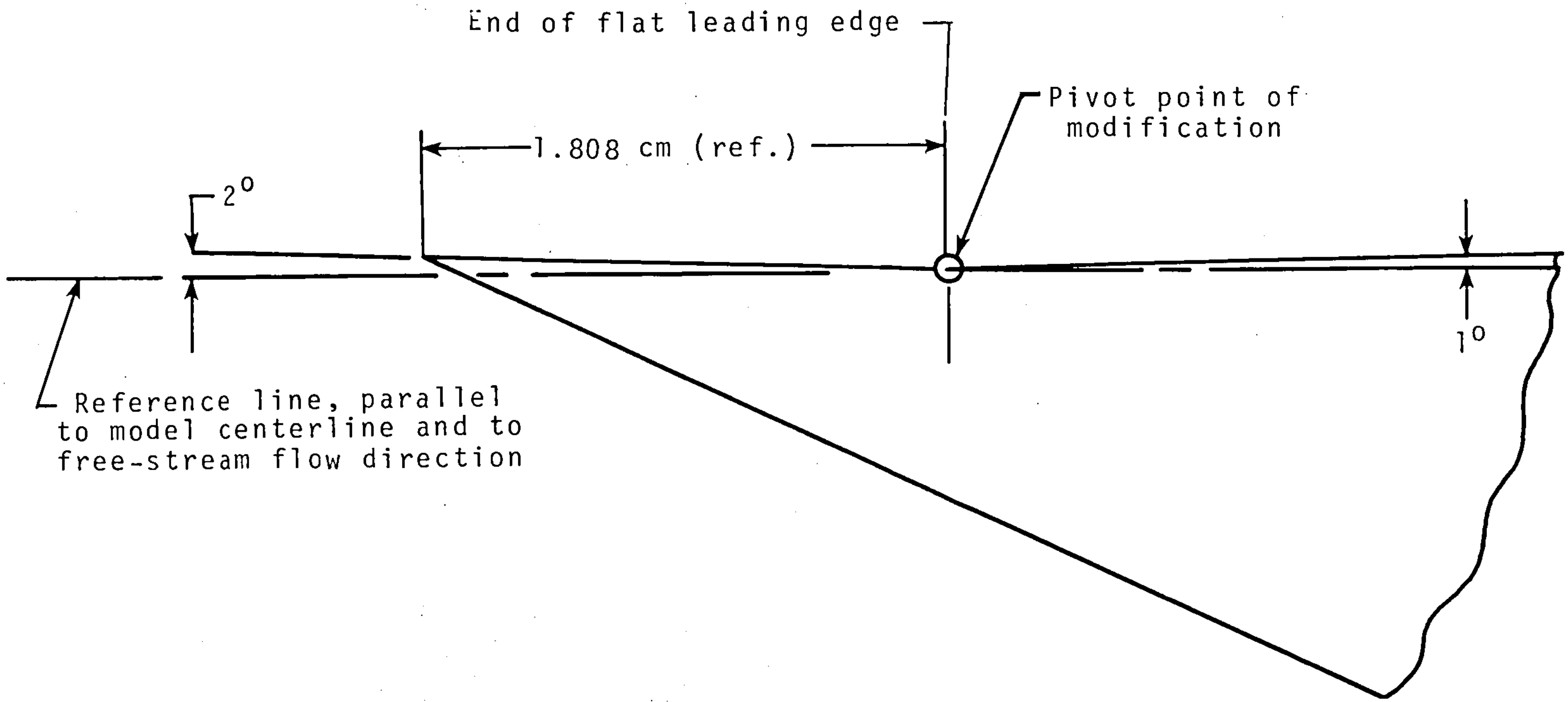
(b) Rod-wall sound shield. Mod V with plenum ducts removed.

Figure 1.- Continued.



(c) Cutaway view of rod-wall sound shield. Mod I.

Figure 1.- Continued.



(d) Modified leading edge of model showing 2° expansion angle.

Figure 1.- Concluded.

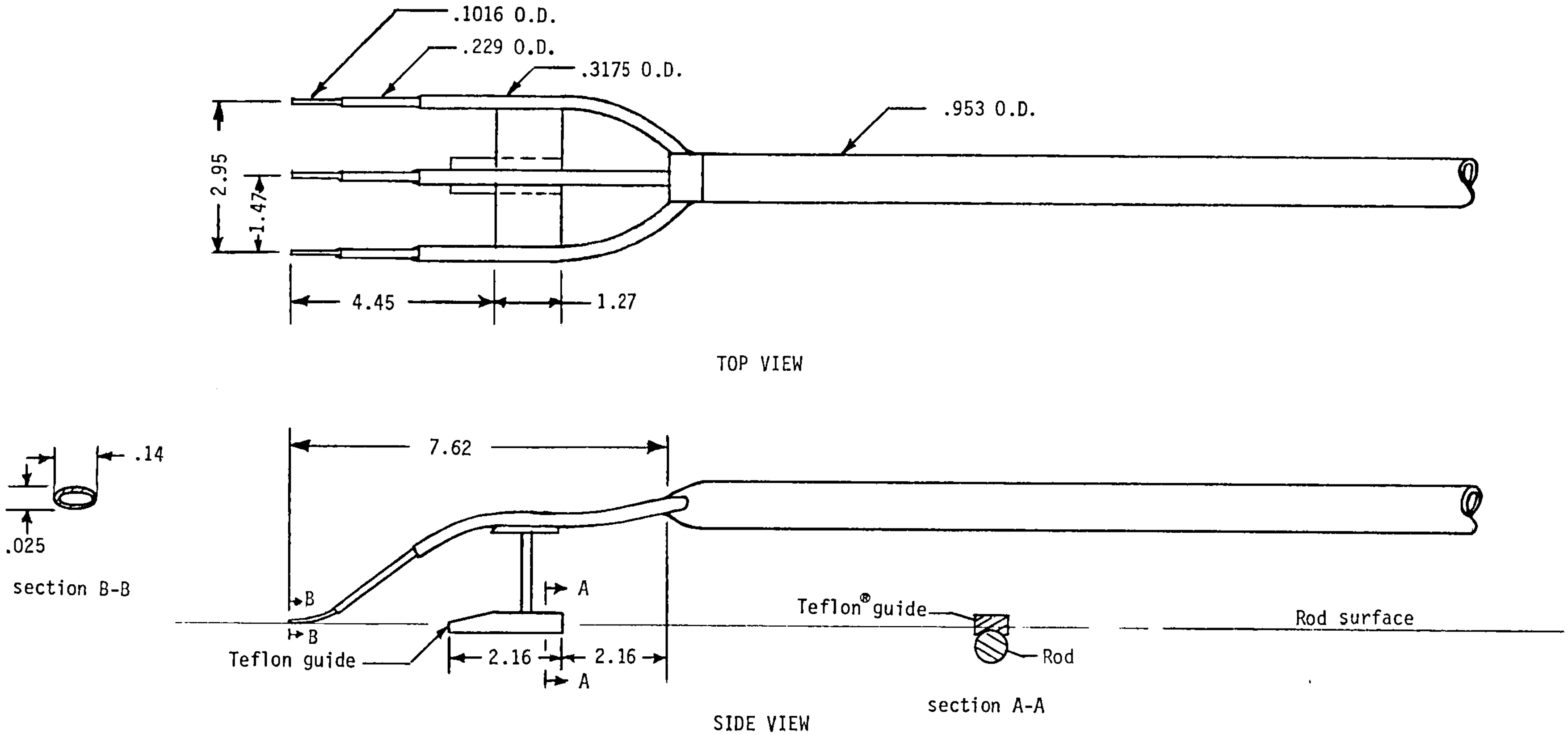
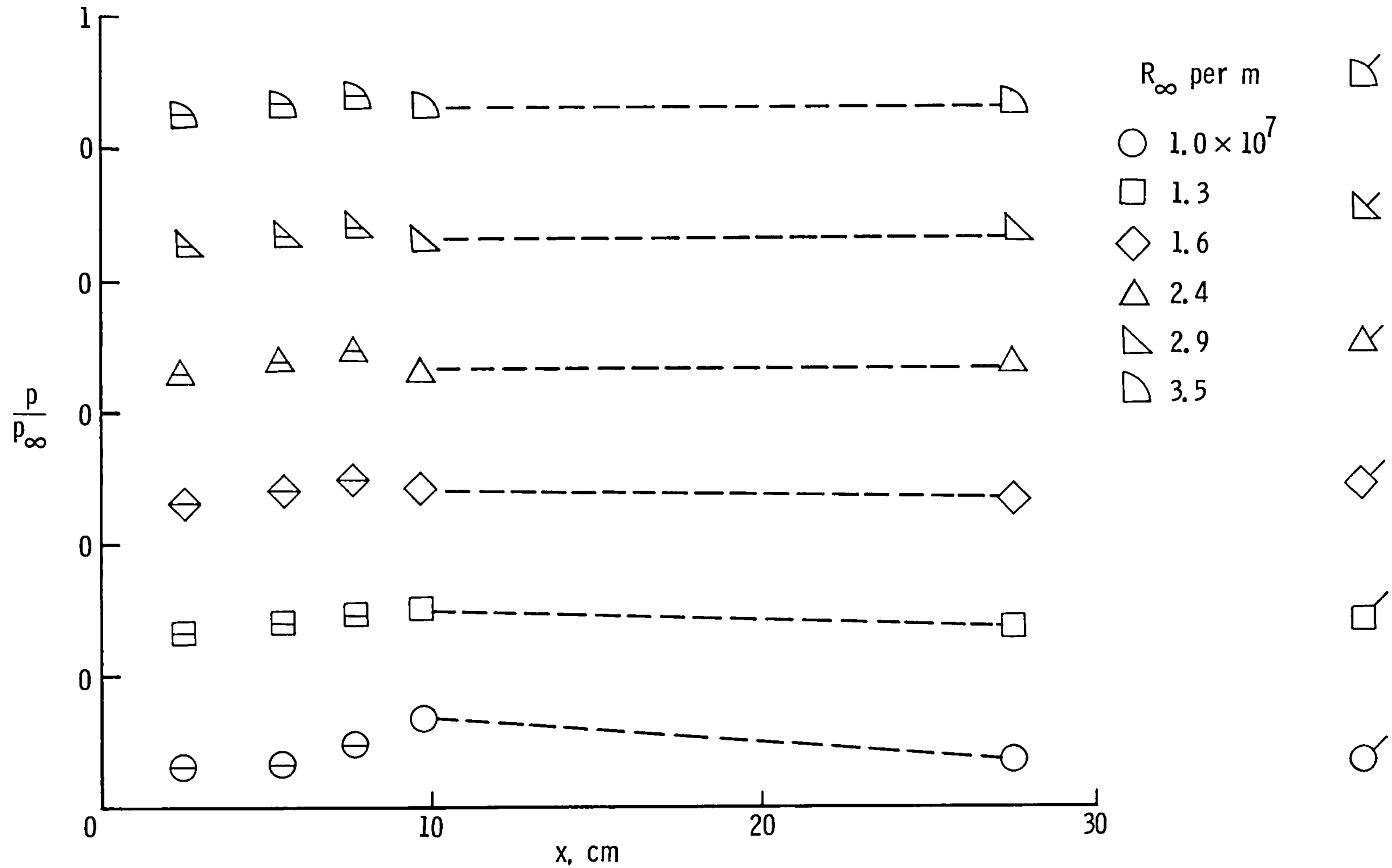
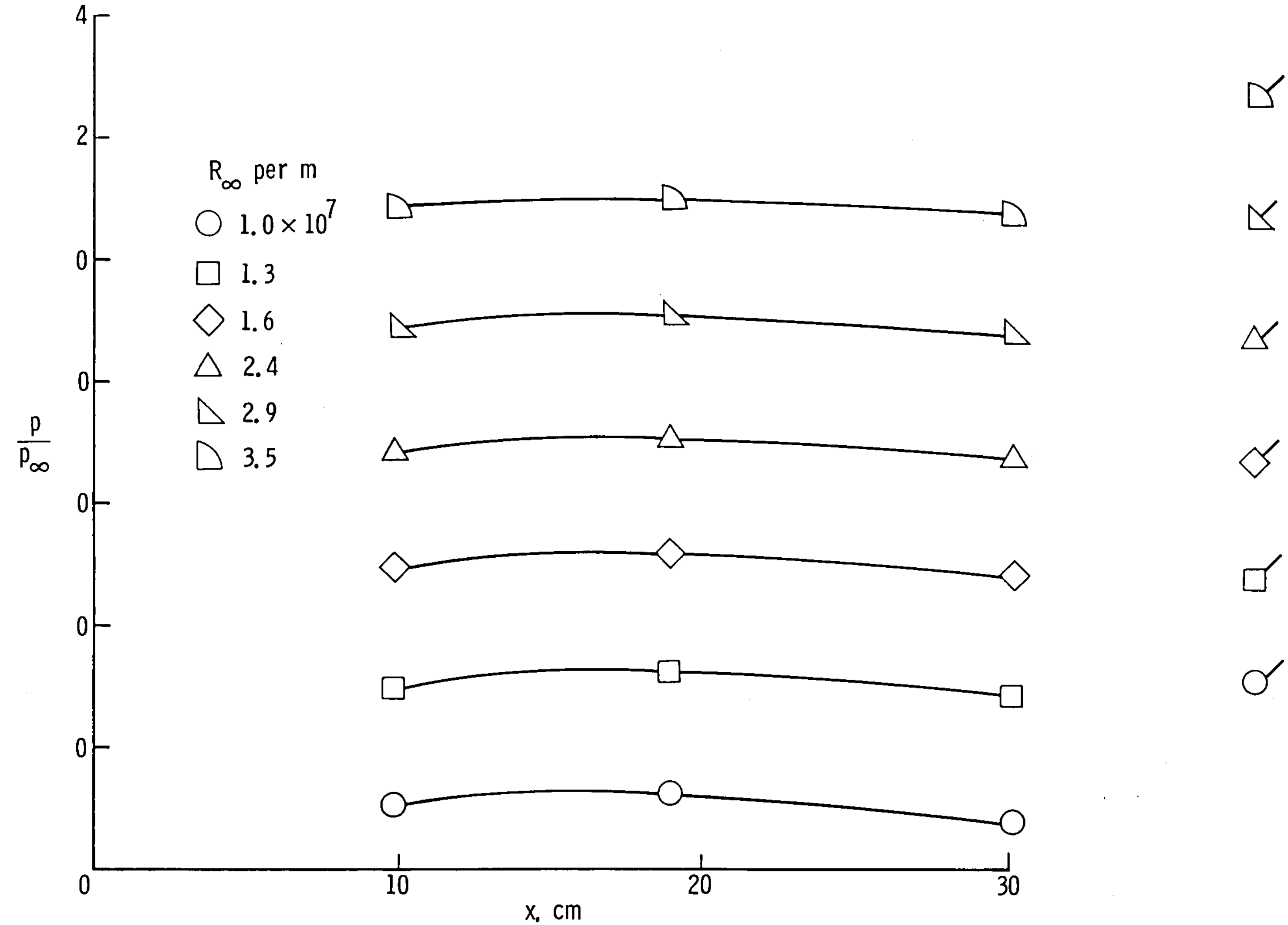


Figure 2.- Pressure probe. Three-tube surface pitot rake. All dimensions are in centimeters. Teflon: registered trademark of E. I. du Pont de Nemours & Co., Inc.



(a) Plain symbols represent bottom surface of rods. Flagged symbols represent the plenum at x = 23.37 cm. Barred symbols represent plenum pressure at front of model.

Figure 3.- Static pressure on rod-wall sound shield. Mod VI.



(b) Plain symbols represent top surface of rods. Flagged symbols represent p_{box}/p_∞ upstream of nozzle.

Figure 3.- Concluded.

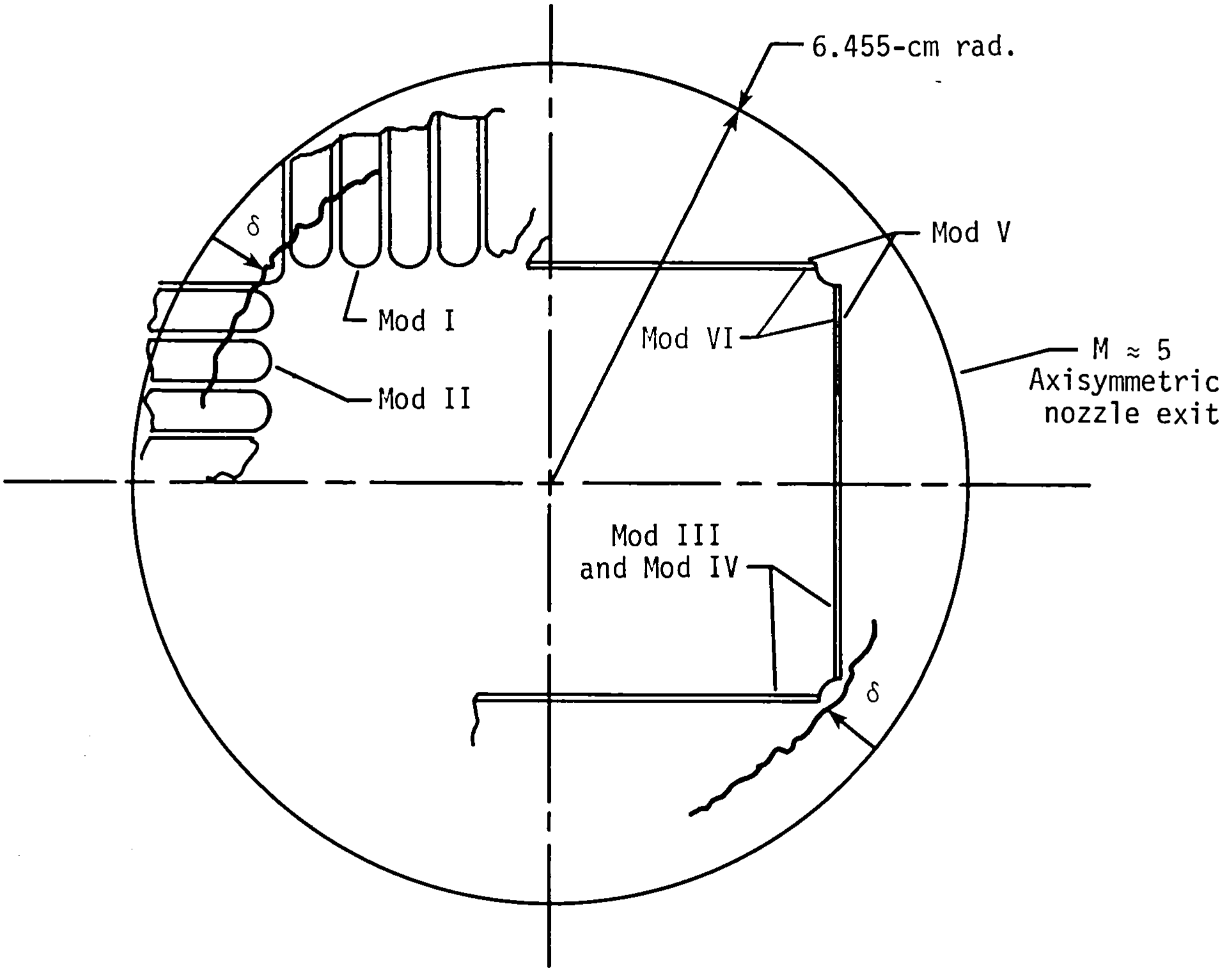
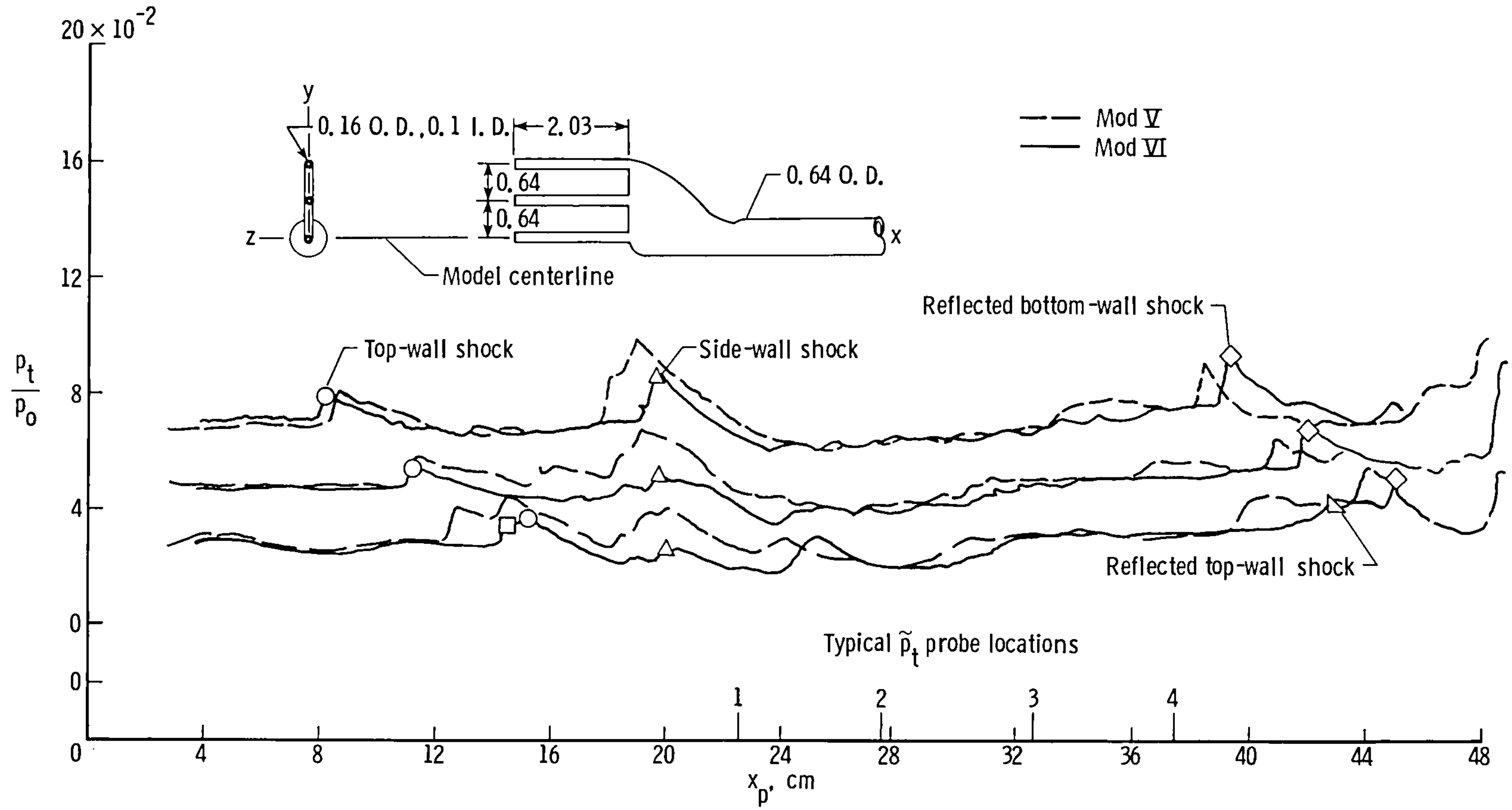
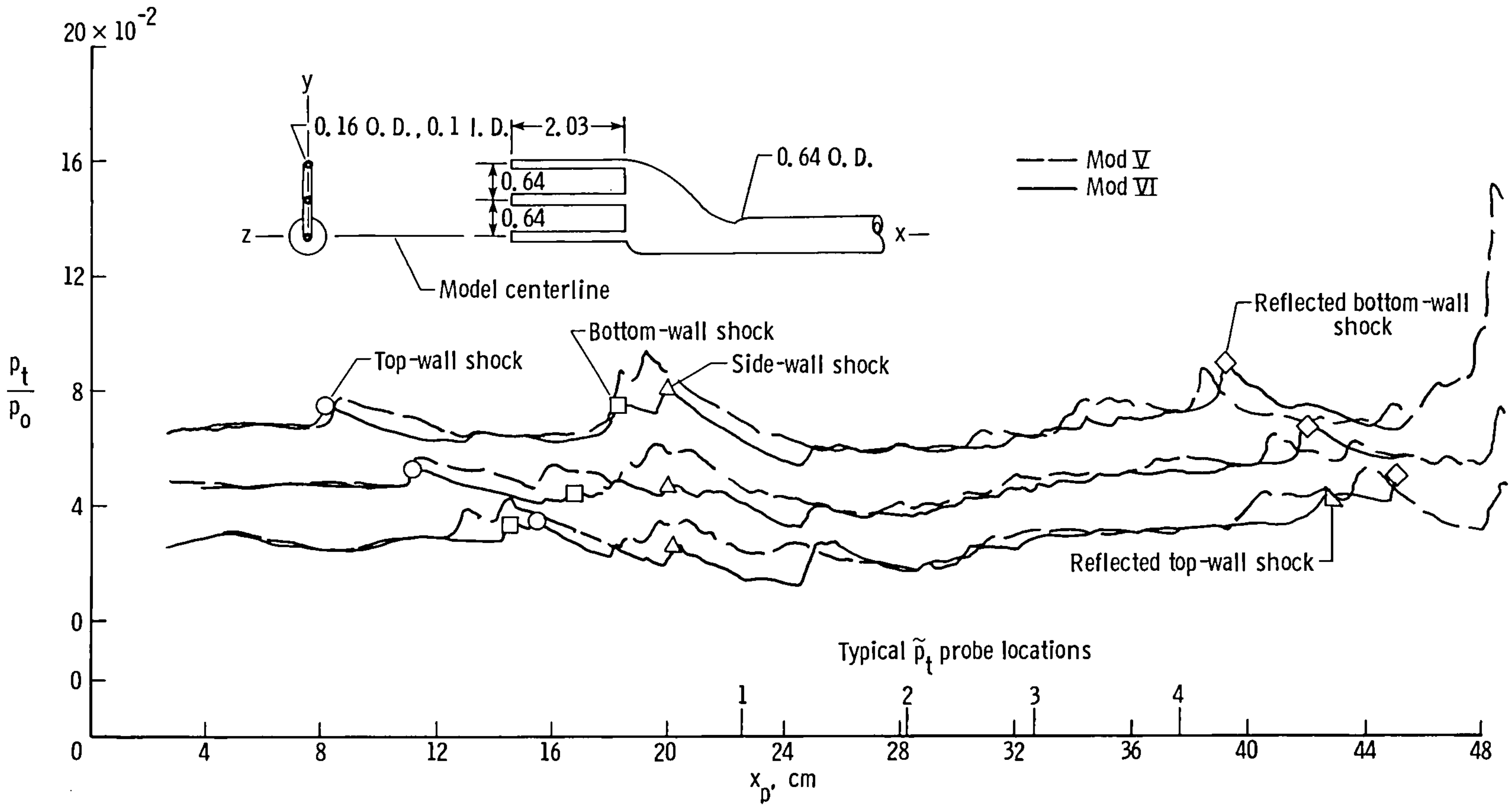


Figure 4.- Leading edges of rod-wall shields compared with nozzle exit. Inside dimensions of leading edges: Mods IV and V were 8.687 cm wide by 6.477 cm high; Mod V was 8.890 cm wide by 6.680 cm high; Mod VI was 8.76 cm wide by 6.55 cm high. $\delta \cong 1$ cm (ref. 4).



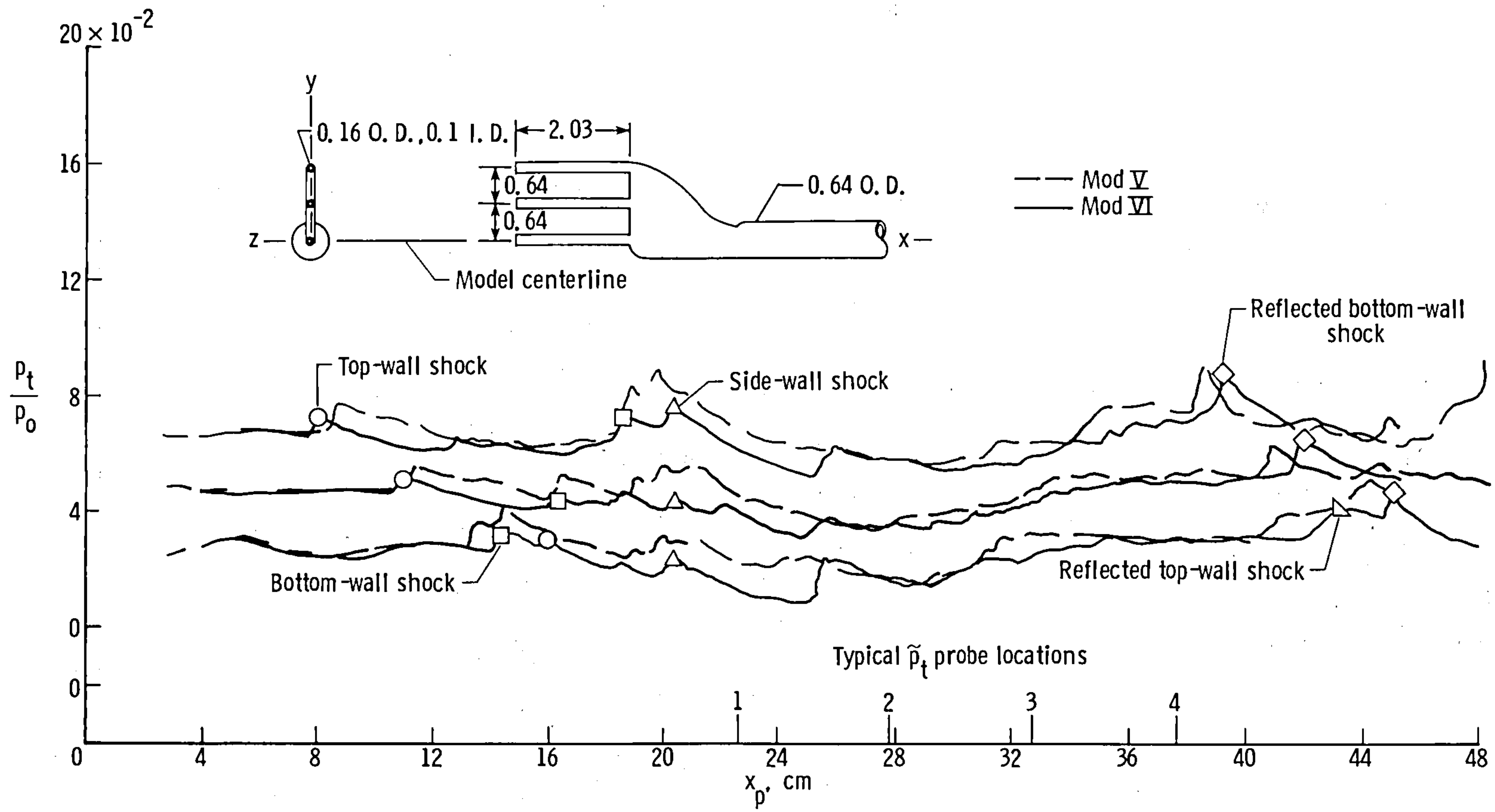
(a) $R_\infty \approx 1.0 \times 10^7$ per meter.

Figure 5.- Mean pitot pressures in rod-wall sound shield. Three-probe rake vertical; Mod VI; $M_\infty \approx 4.9$.



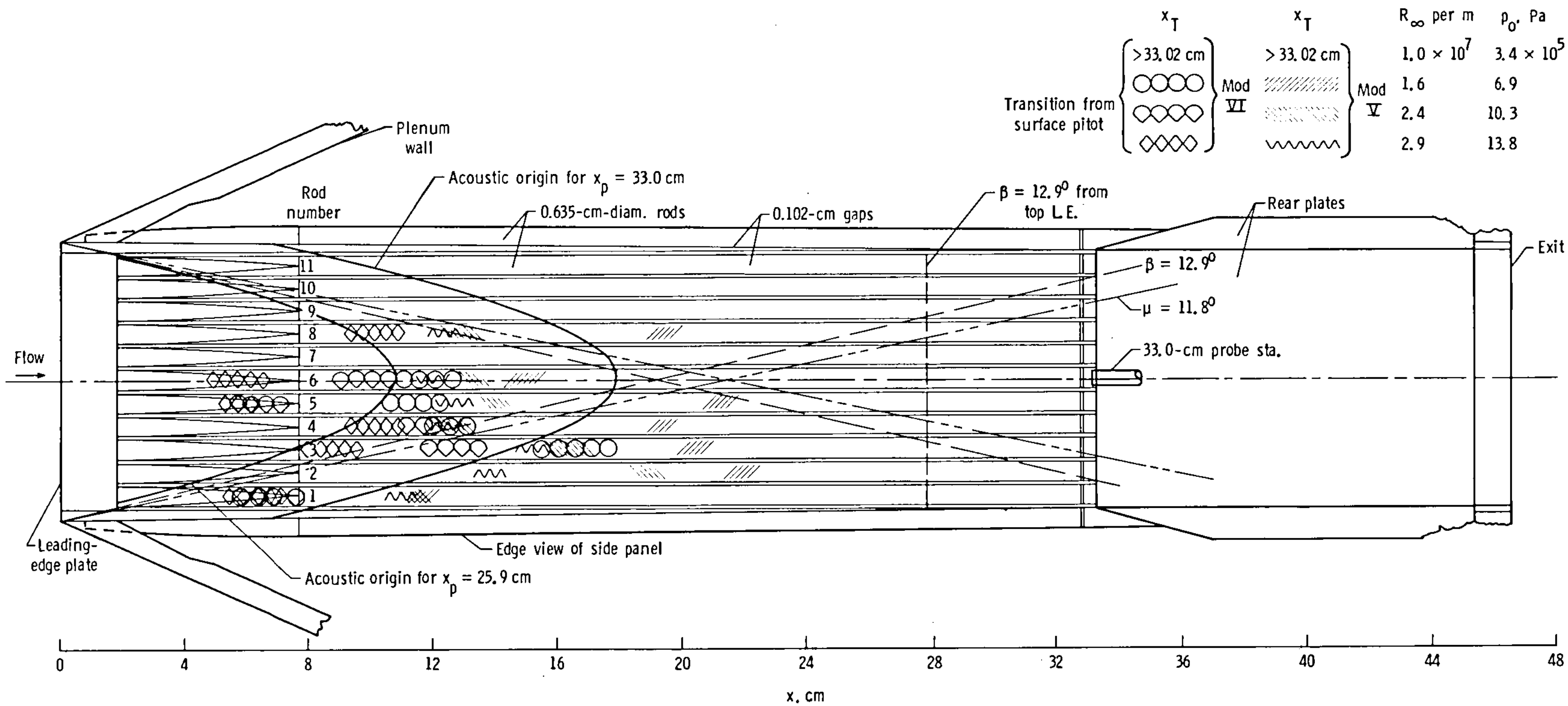
(b) $R_\infty \approx 1.6 \times 10^7$ per meter.

Figure 5.- Continued.



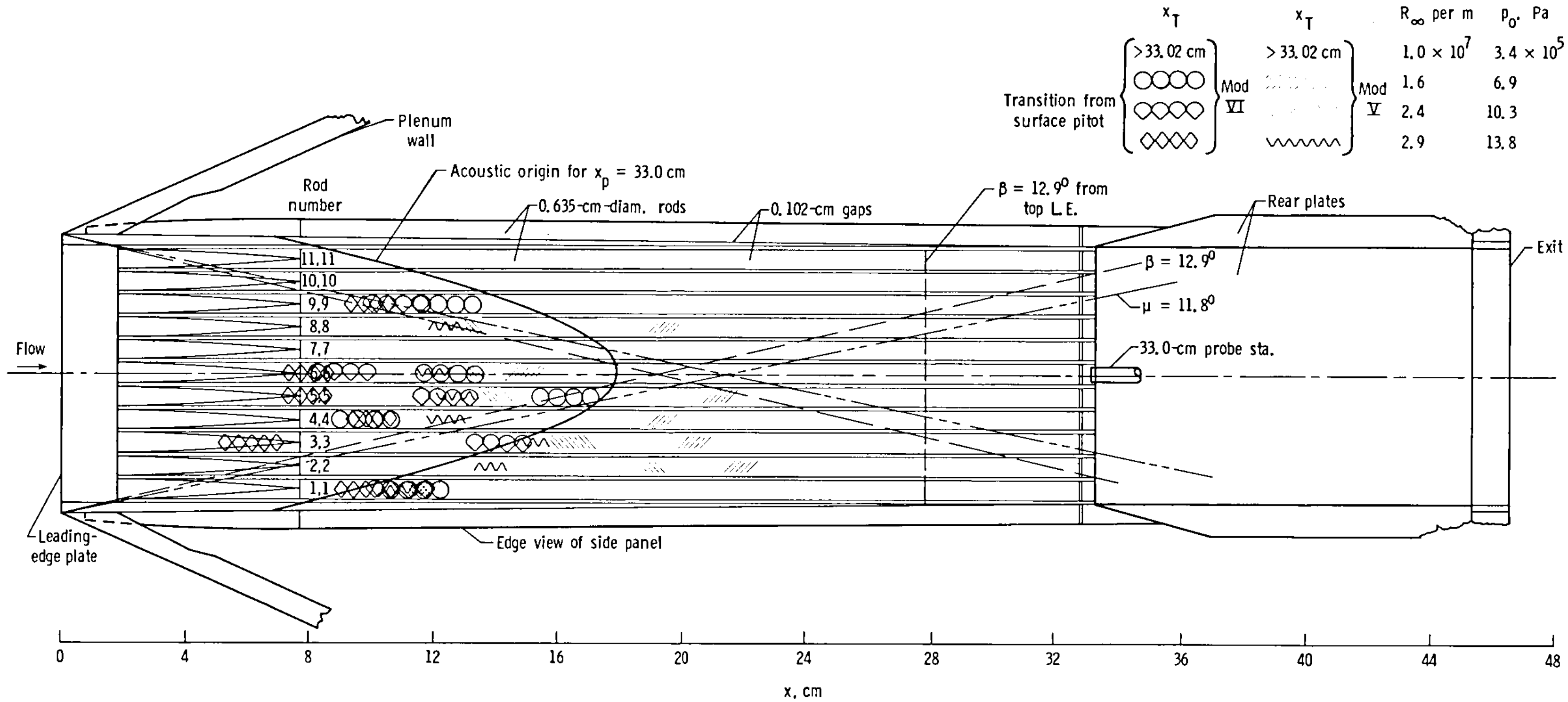
(c) $R_\infty \approx 2.9 \times 10^7$ per meter.

Figure 5.- Concluded.



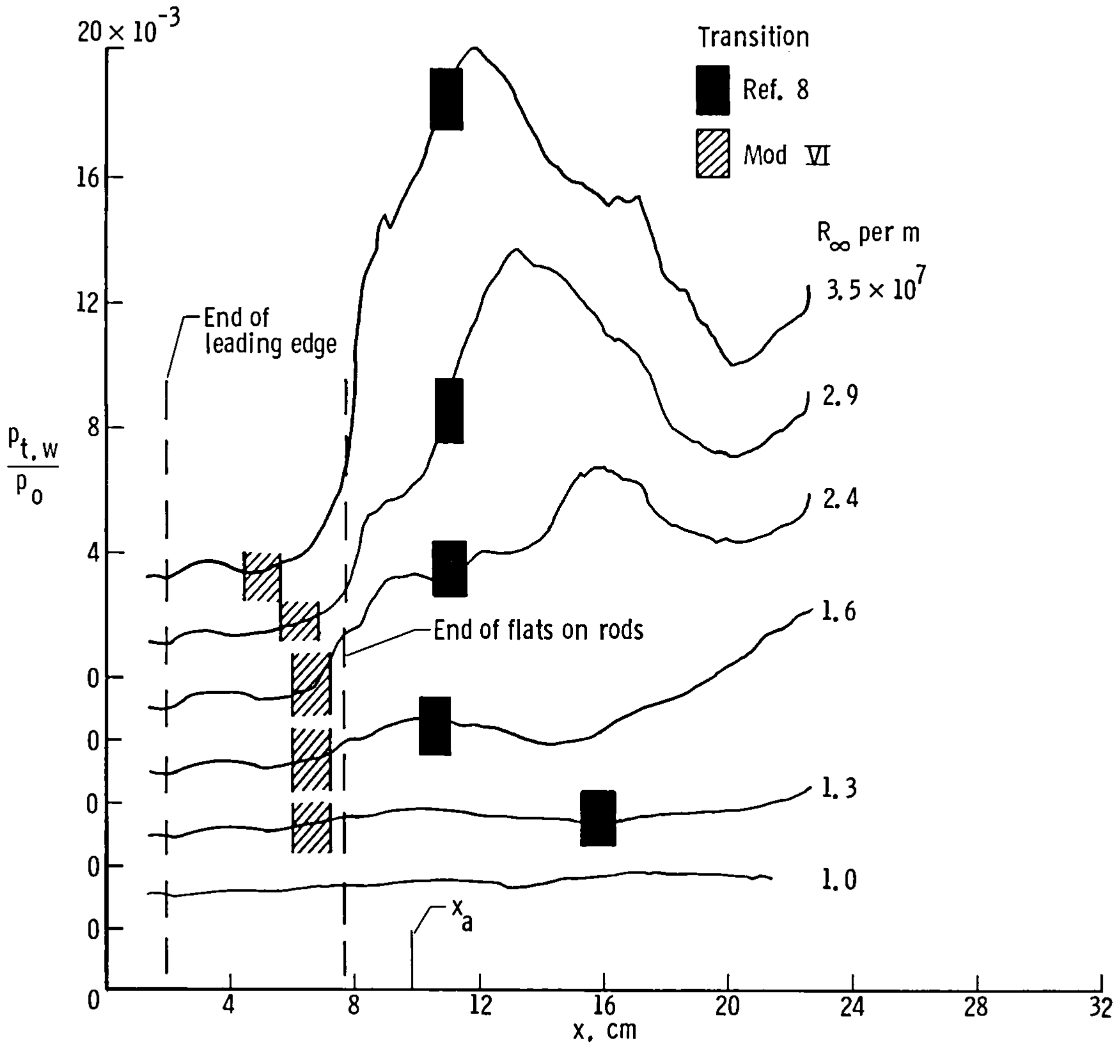
(a) Bottom panel.

Figure 6.- Panel of shield with projected location of side-wall shocks and acoustic-origin locus for a point probe at x_p = 33.0 cm and 25.9 cm. Mod VI.



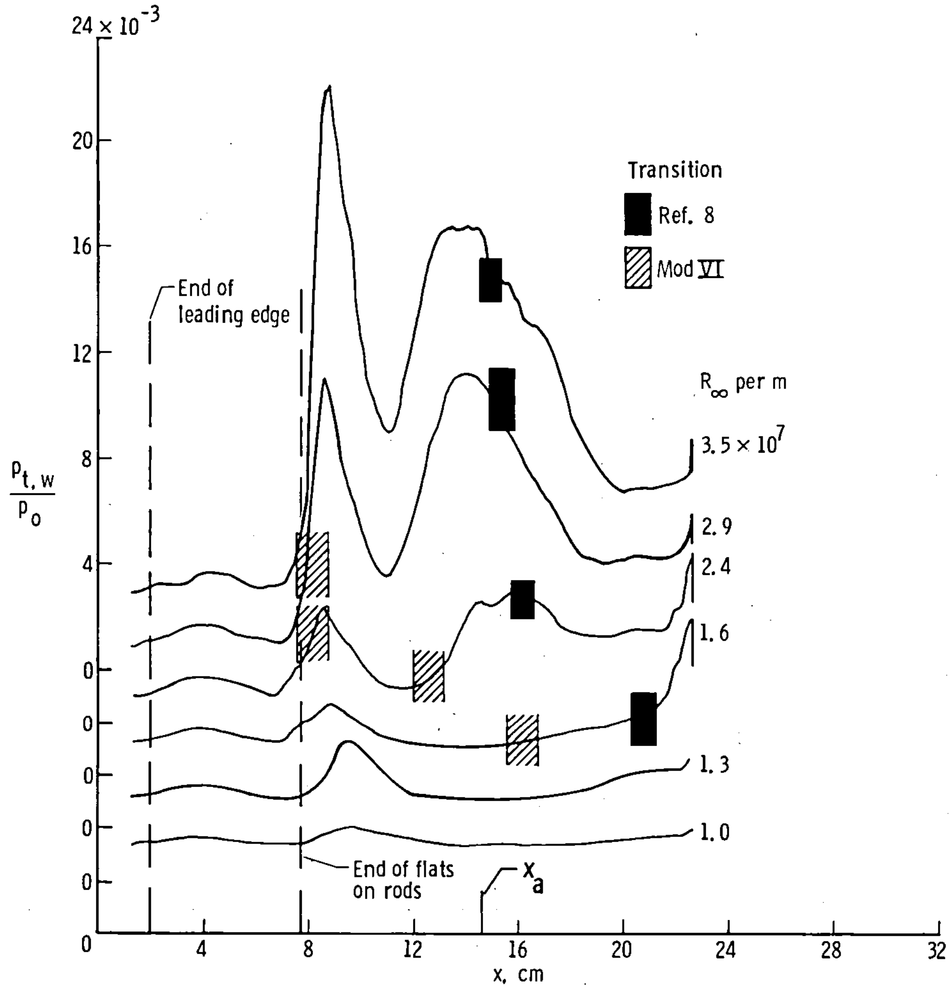
(b) Top panel.

Figure 6.- Concluded.



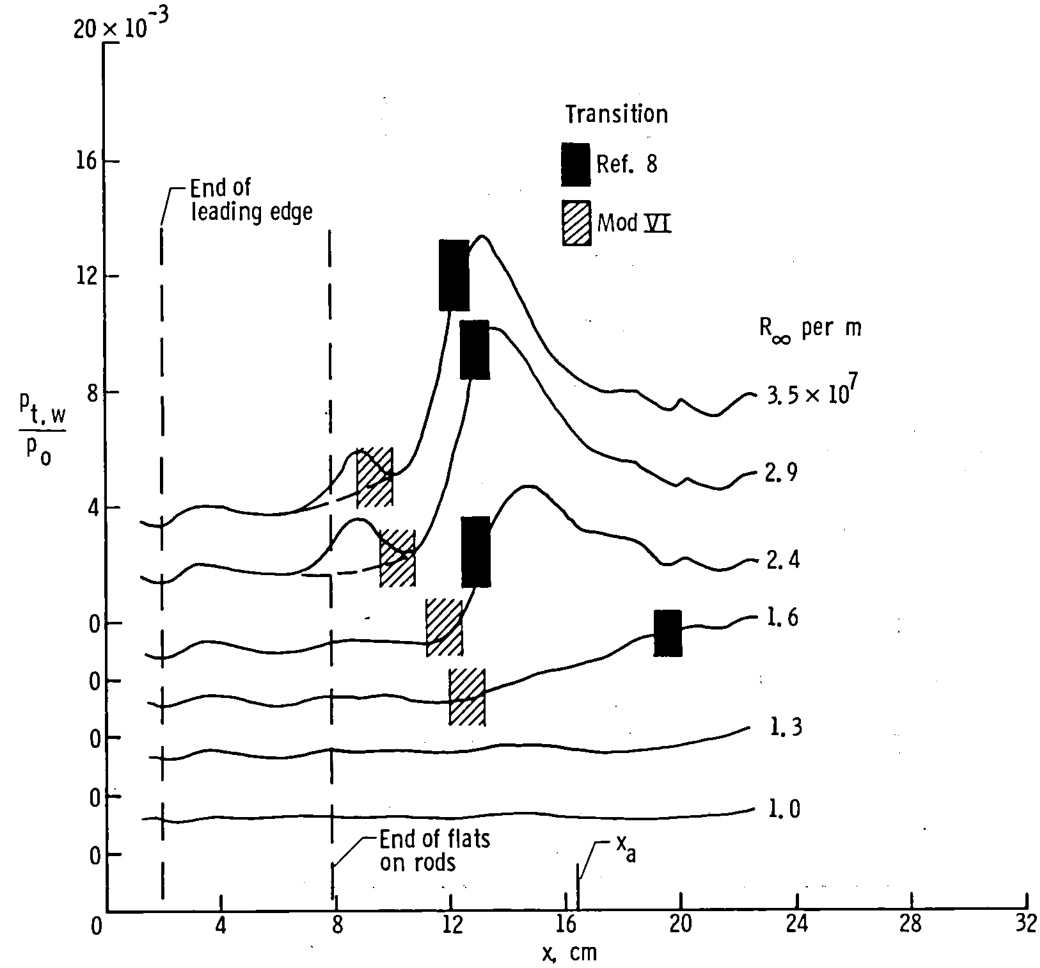
(a) Rod 1.

Figure 7.- Typical surface pitot pressures on bottom panel of rod-wall sound shield. Mod VI; $M_\infty \approx 4.9$.



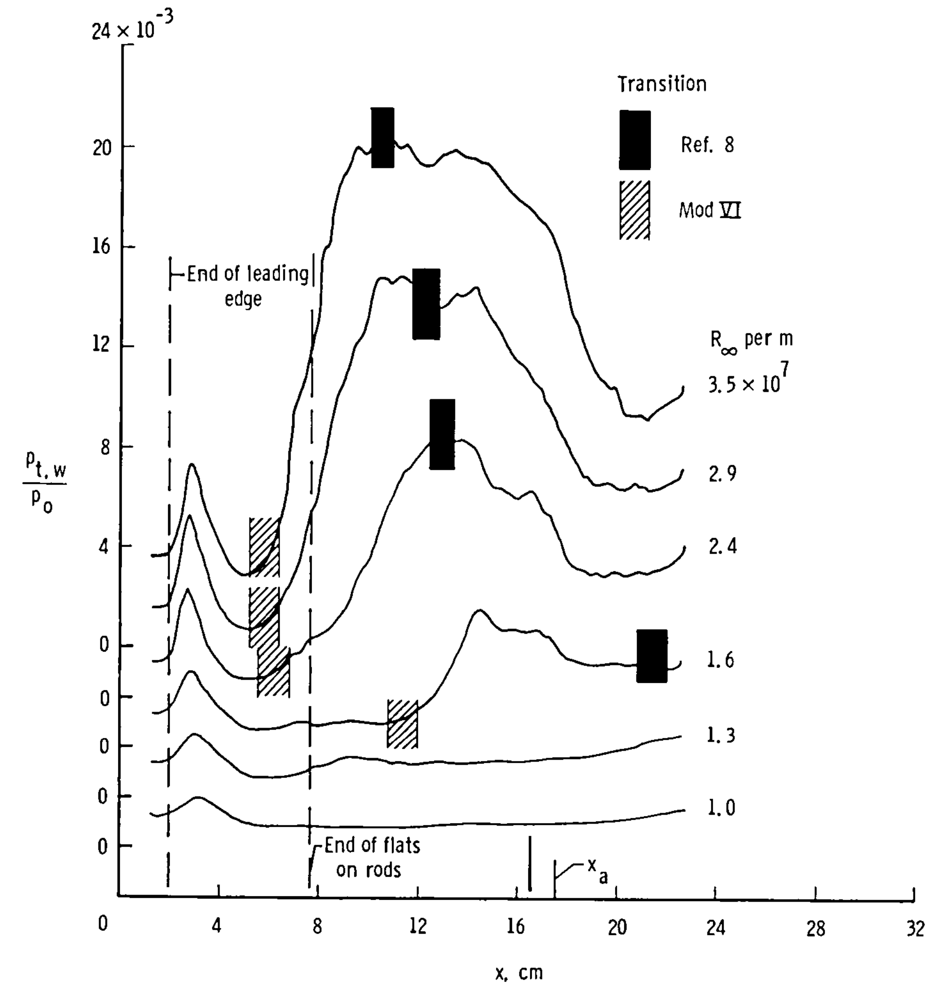
(b) Rod 3.

Figure 7.- Continued.



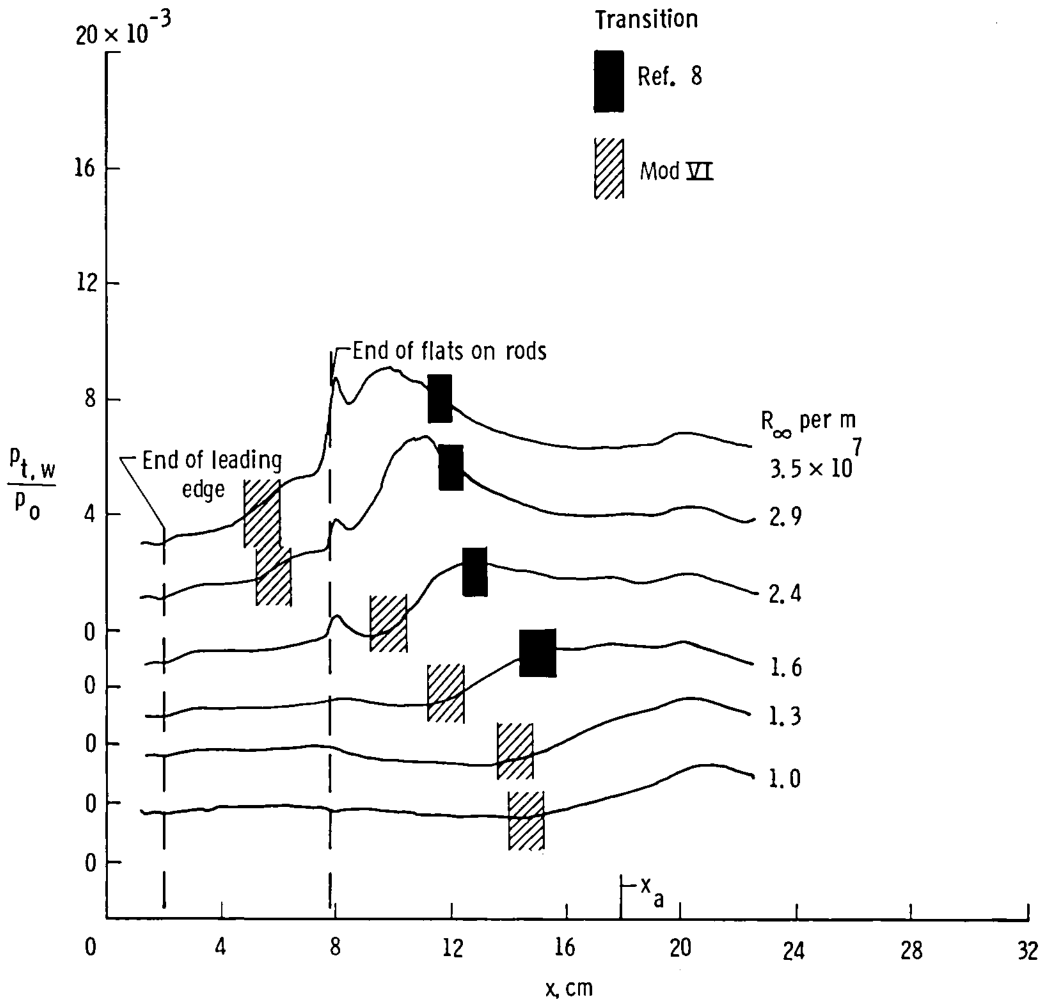
(c) Rod 4.

Figure 7.- Continued.



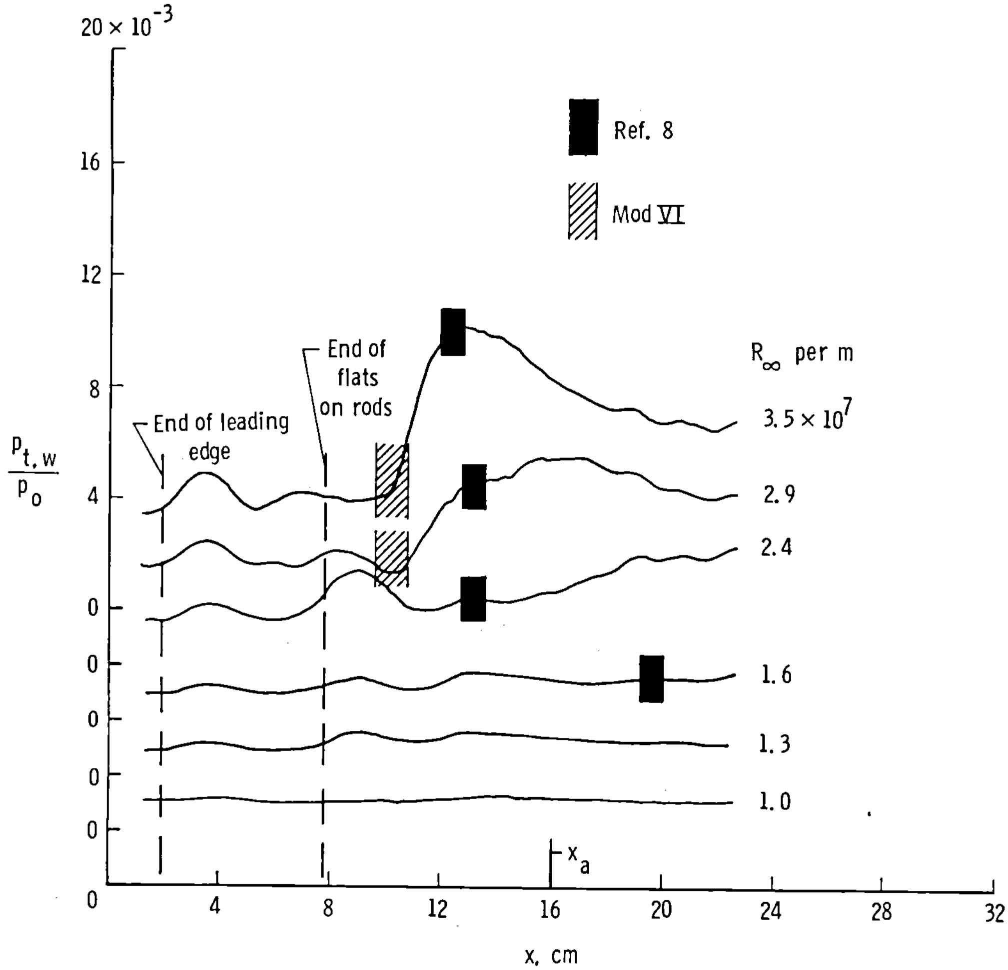
(d) Rod 5.

Figure 7.- Continued.



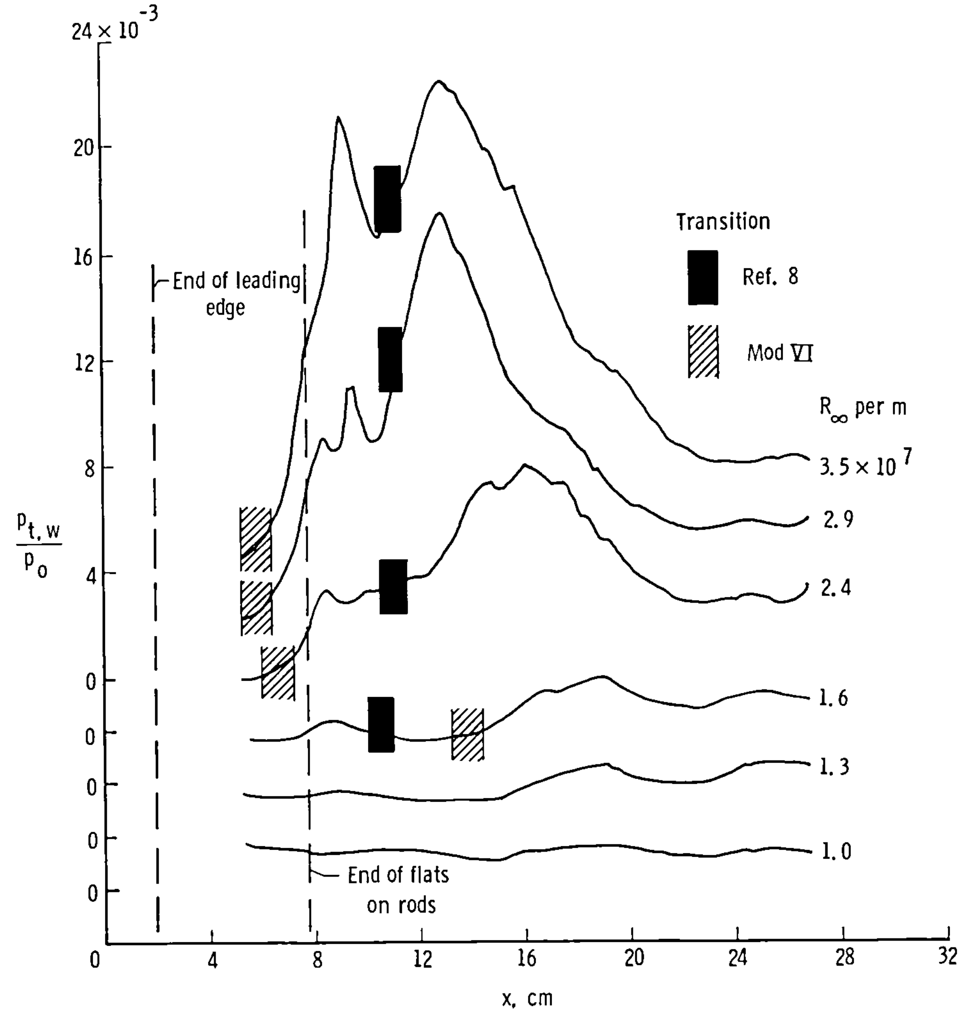
(e) Rod 6.

Figure 7.- Continued.



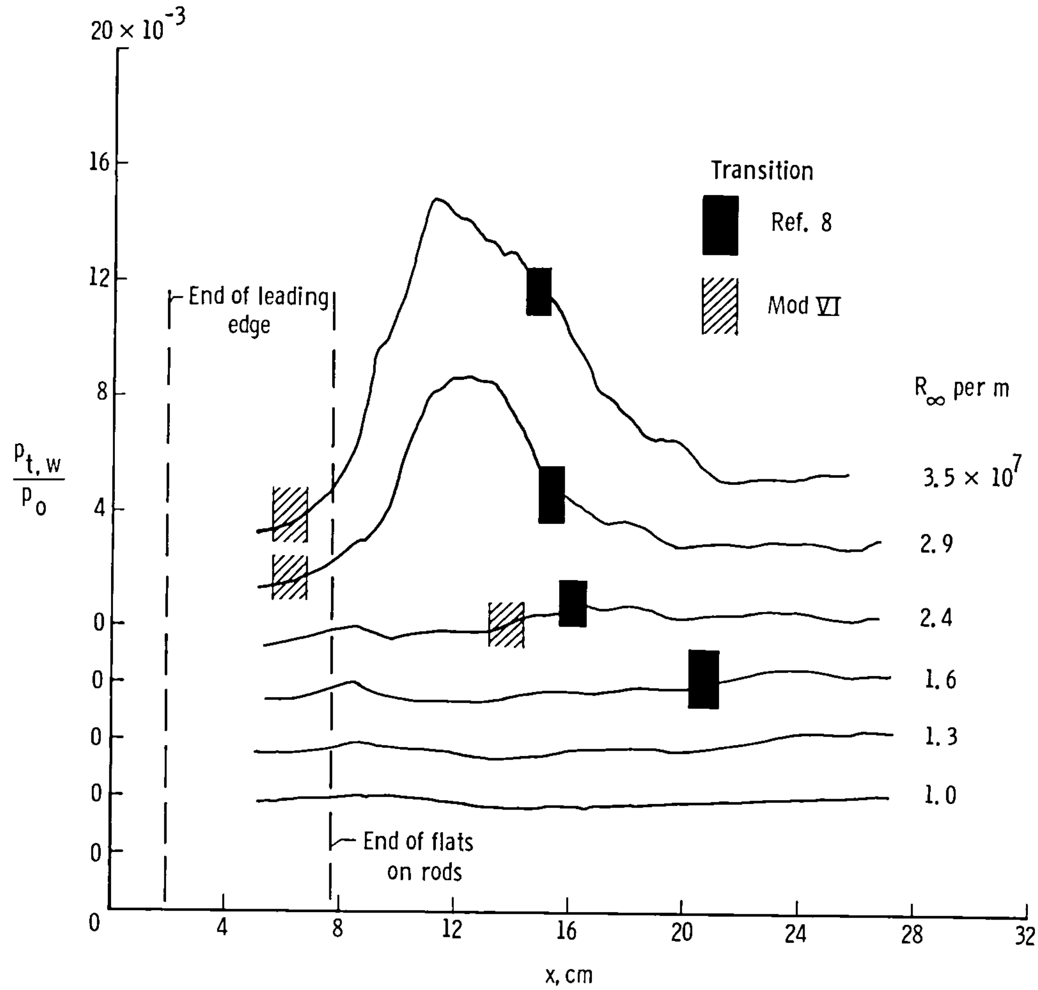
(f) Rod 8.

Figure 7.- Concluded.



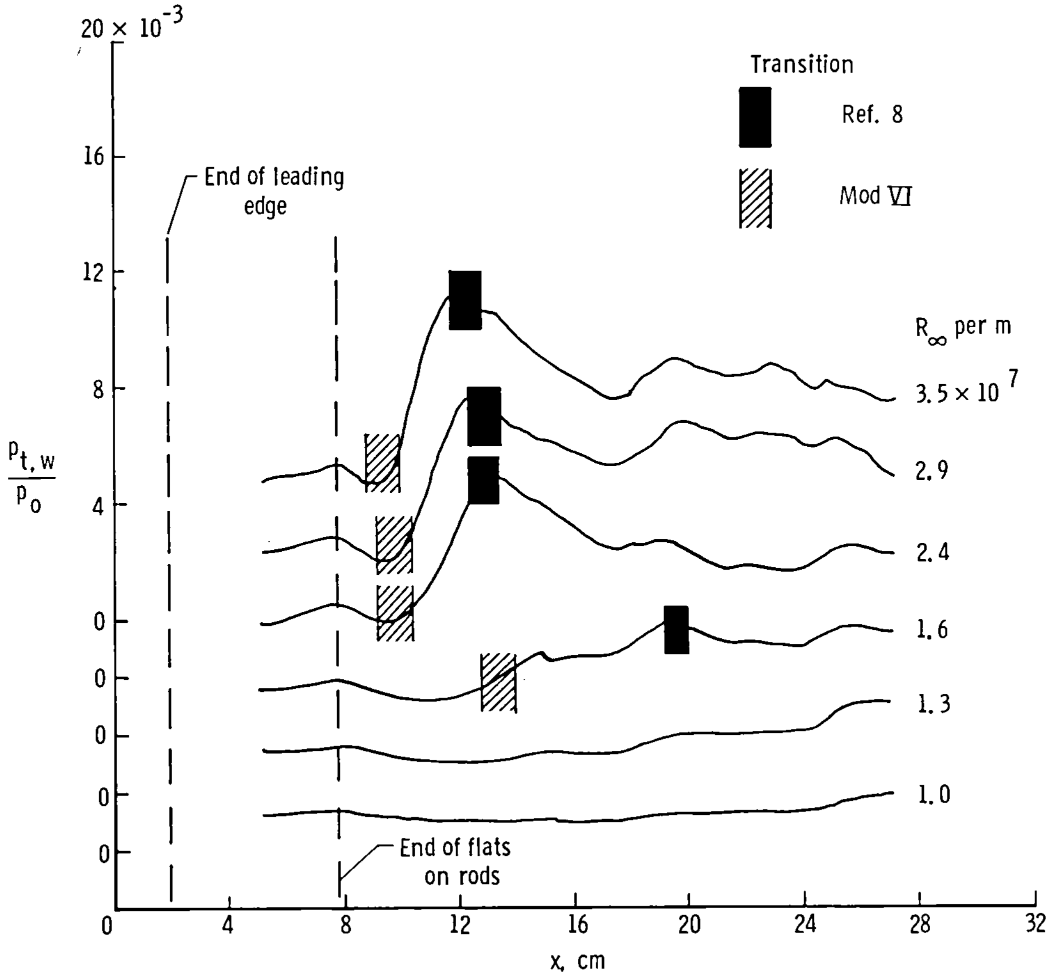
(a) Rod 1,1.

Figure 8.- typical surface pitot pressure on top panel of rod-wall sound shield. Mod VI; $M_\infty \approx 4.9$.



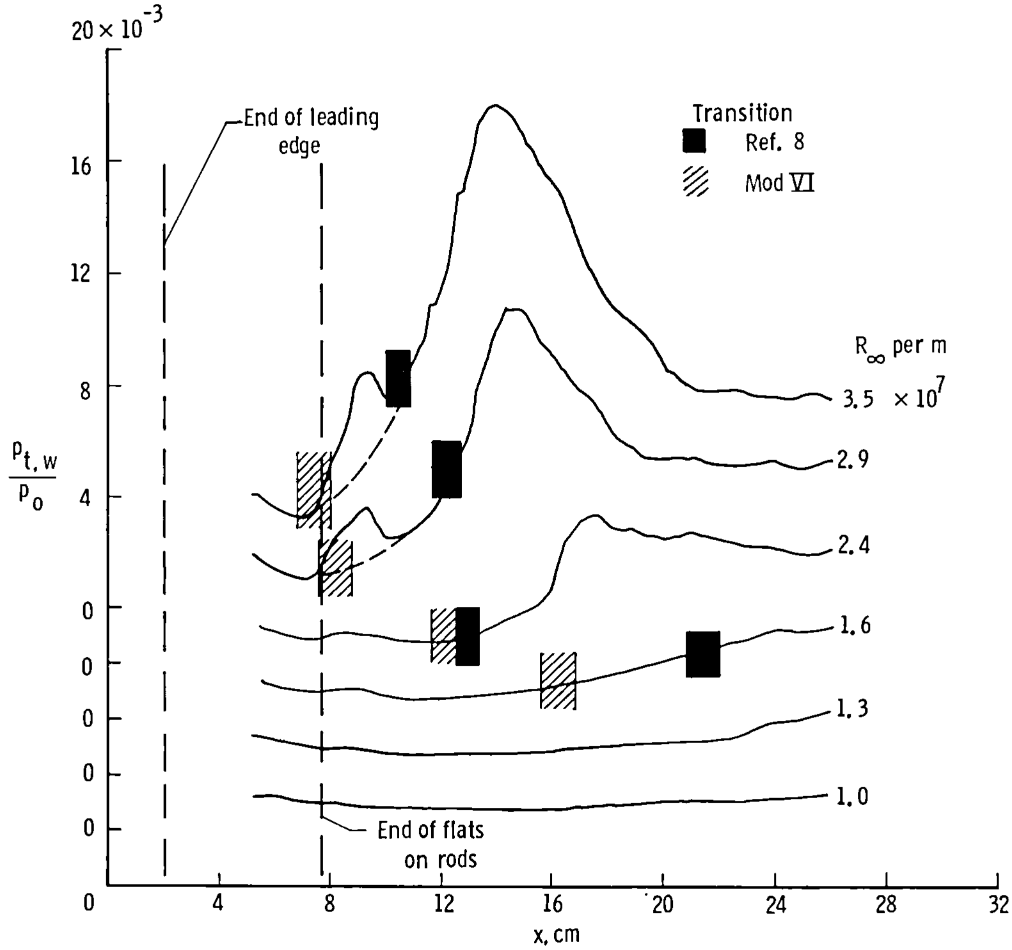
(b) Rod 3,3.

Figure 8.- Continued.



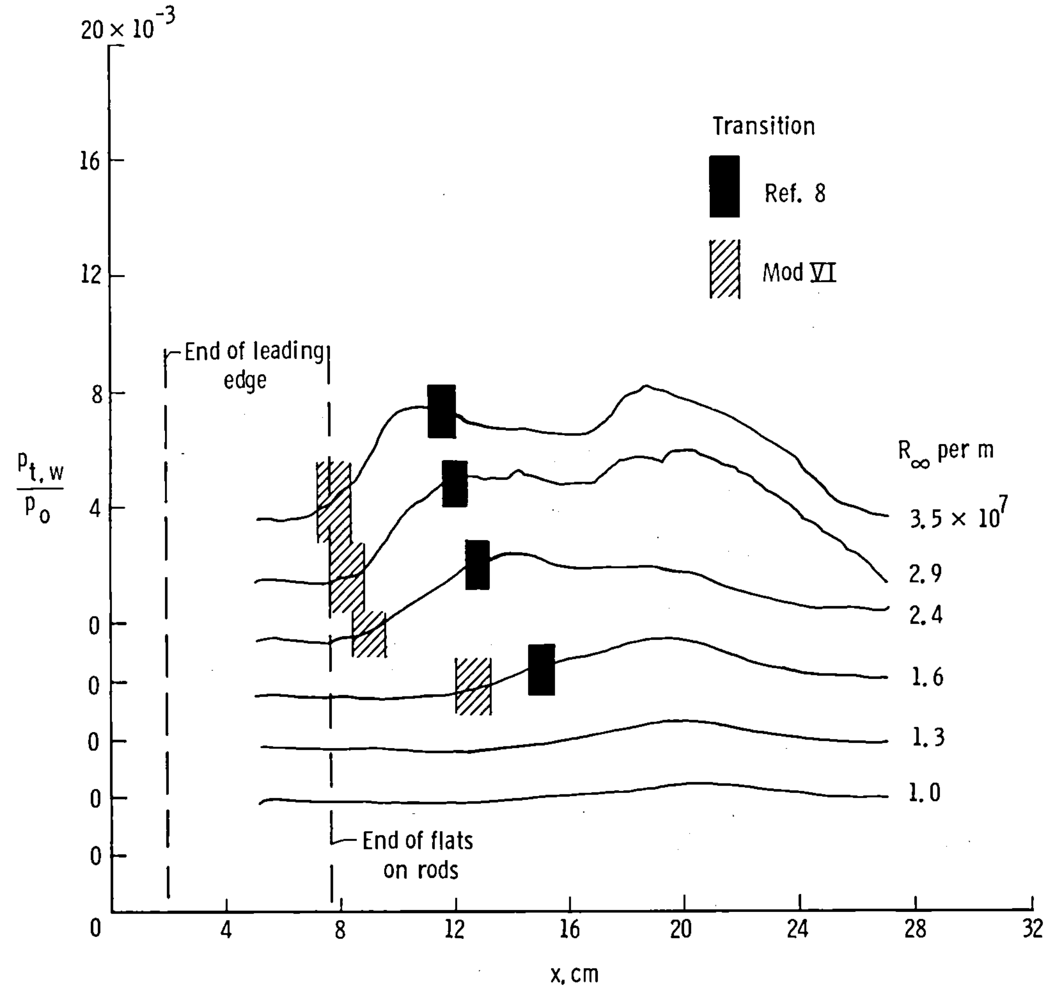
(c) Rod 4,4.

Figure 8.- Continued.



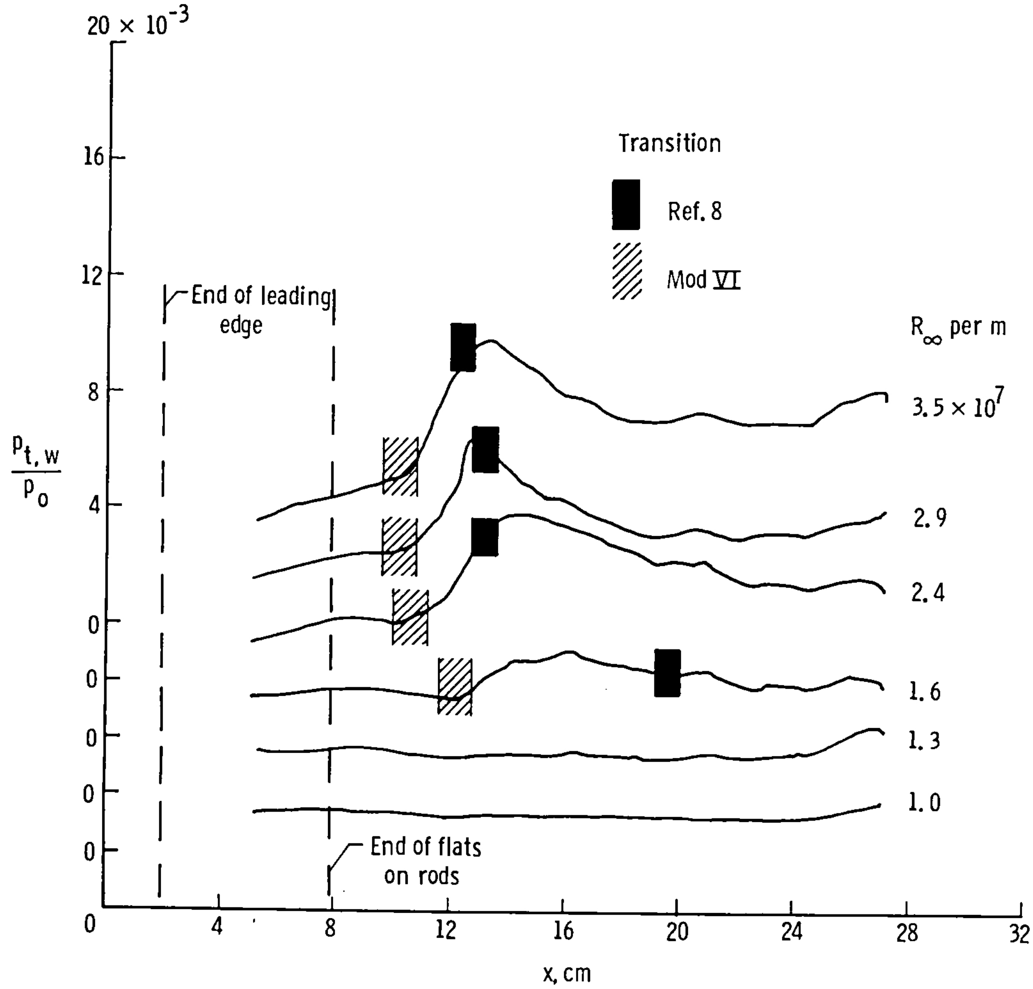
(d) Rod 5,5.

Figure 8.- Continued.



(e) Rod 6,6.

Figure 8.- Continued.



(f) Rod 8,8.

Figure 8.- Concluded.

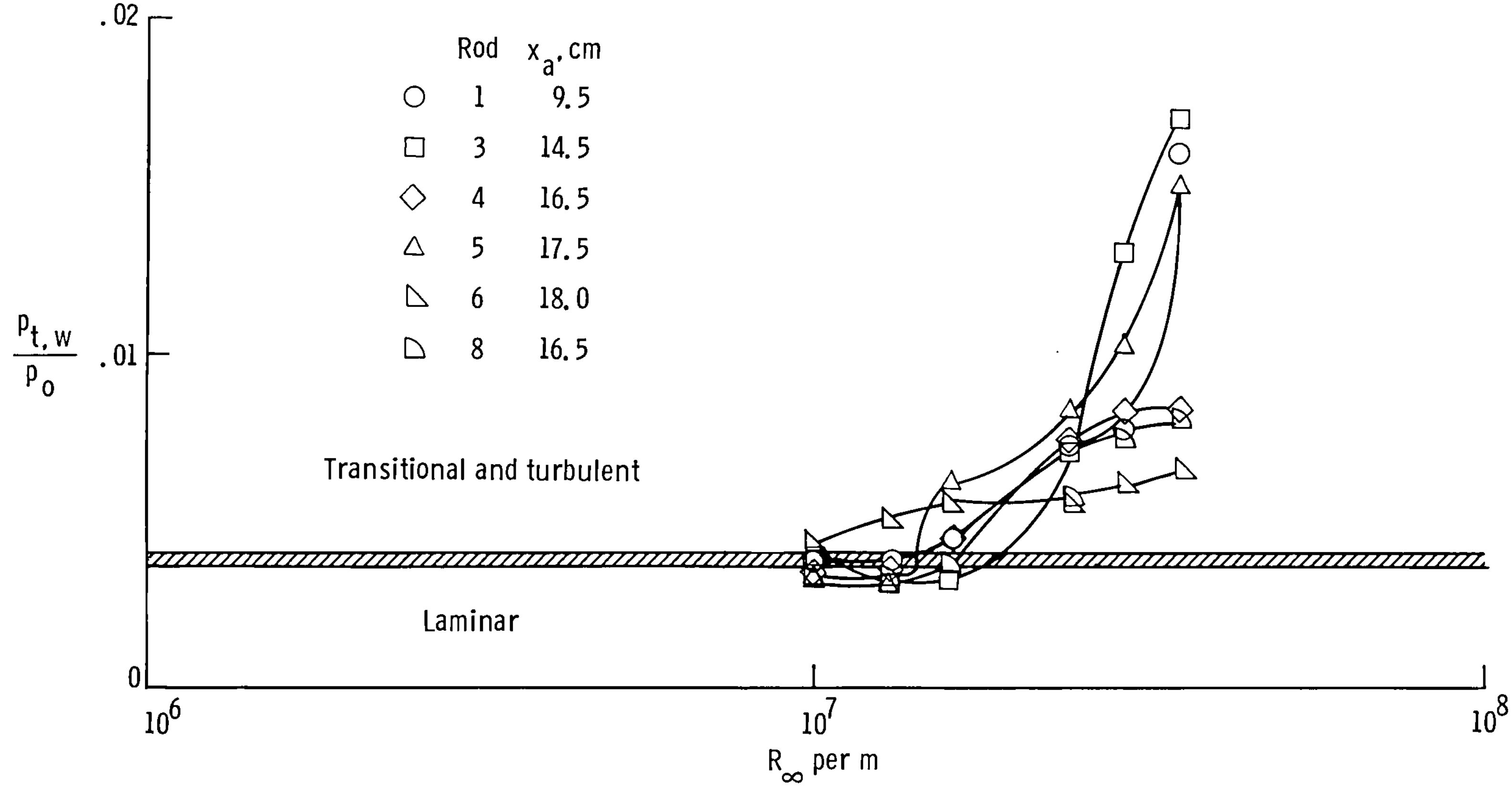


Figure 9.- Variation of surface pitot pressure with Reynolds number on bottom panel of rod-wall sound shield at acoustic origin for x_p = 33.0 cm.

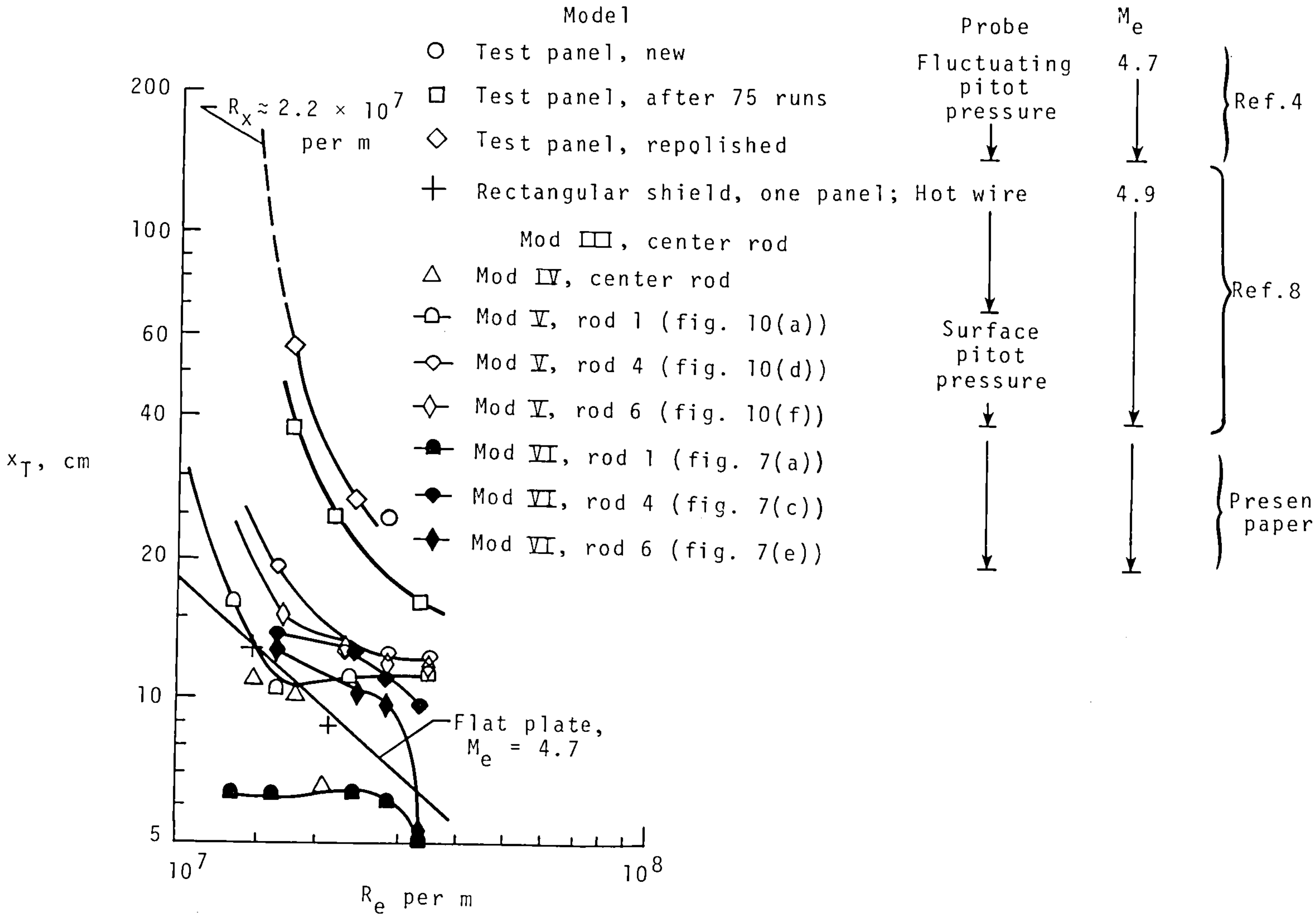


Figure 10.- Transition on rod walls.

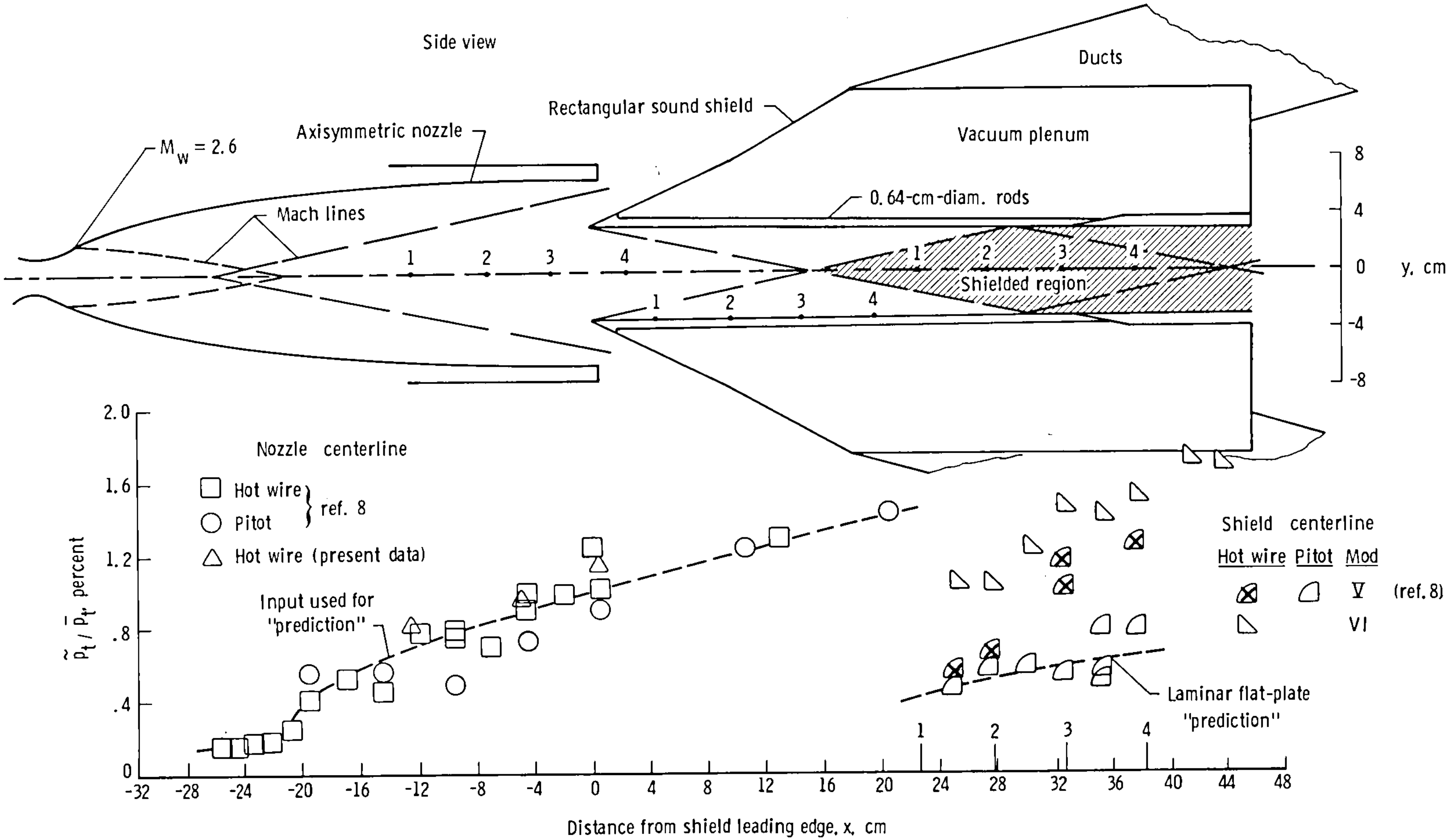


Figure 11.- Normalized pitot-pressure fluctuations along centerline of rectangular rod-wall sound shield. Diameter of fluctuating pitot-pressure probe was 0.635 cm, Mod VI; $M_\infty = 4.9$; $R_\infty = 1.5 \times 10^7$ per meter.

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16. Abstract

A modified version of a rod-wall sound shield was tested in the Mach 5 pilot quiet tunnel at the Langley Research Center over a range of unit Reynolds numbers from 1.0×10^7 to 3.5×10^7 per meter. The model was modified by inclining the leading-edge plates to produce an initial 2° expansion for the purpose of ascertaining the sensitivity of boundary-layer transition to leading-edge disturbances. Rod-surface pitot pressures, mean free-stream pitot pressures, and static pressures on the rods and plenum walls were measured. Hot-wire measurements were also made in the model and nozzle free stream at a unit Reynolds number of 1.5×10^7 per meter. The surface pitot pressures indicated that transition was much farther forward than for the previous tests due to the leading-edge modification and minor fabrication flaws in the model.

Early boundary-layer transition on the rods was confirmed by hot-wire measurements which showed much higher noise levels in the free-stream shield flow when compared with results from previous tests. Mean pitot-pressure surveys within the shielded region inside the model indicated that there was an overexpansion and recompression that would effectively limit the streamwise length of undisturbed flow to about 13 cm along the centerline.

17. Key Words (Suggested by Author(s))
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